A Library Based Approach for Exploring Style in Preliminary Ship Design

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A thesis submitted for the degree of Doctor of Philosophy

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December 2010

I, Timothy Patrick McDonald confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

The unique decision making environment that occurs in ship concept design prevents a full exploration of possible solution styles. However, alternative styles present distinct advantages in certain situations. This is particularly true for different hullform styles which can give significant performance benefits. To fully capitalise upon these alternatives, a comprehensive exploration should occur at the outset of the design process. Current ship design methods have been found to limit the designer's ability to rapidly explore a large number of radically differing alternatives. This is a consequence of a common requirement for the early selection of design styles. Clearly, some approach able to support the designer in exploring alternative styles early in the design process would offer the designer significant advantages.

This thesis begins with the identification of a gap in the design methods currently available to the designer selecting hullform style early in the ship design process. It details a design approach aimed at closing this gap while targeting the early design stages of naval ships. A review of wider engineering design research has highlighted several promising models of design theory, knowledge and technology that could be usefully applied to this problem. Using these models a new Library Based approach has been proposed and developed. This Library Based approach employs decomposition and pre-calculation to create a library of sub-options that can be rapidly examined using a set of initial design requirements to develop a range of possible options. Comparison with a notional optimisation process suggests the proposed approach offers advantages for problems similar in characteristic to the selection of hullform style. The approach is then demonstrated through two example implementations which are applied to the initial design of several naval combatants including an existing design.

The discussion on the proposed approach highlights its strengths and weaknesses compared to two lists of needs for ship concept design tools and also its potential to be employed in concert with other design methods, aiding the necessary decision-making that occurs early in the ship design process. The key conclusion of the research is that the gap in the selection of hullform style can be met through the application of the proposed Library Based approach. Finally, five areas of future research are recommended: exploring extensions of the approach presented able to extrapolate the contents of the library; extend the approach to provide insight into relationships and drivers; investigating alternative technologies for the library; applying parametric design tools to generate library data; and demonstrating links to other design methods.

Dedication

To Manchi, Tom, Mum and Dad.

Acknowledgements

Whilst I as sole author bear full responsibility for the research presented in this thesis, it would not have been possible without the support and encouragement of a large number of individuals both from within the UCL community and beyond.

Firstly, I would like to thank my three successive Ph.D. supervisors: John van Griethuysen, who instigated this research with an initial proposal to explore the comparison of different hull-forms; Simon Rusling, for providing direction and guidance during the majority of the Ph.D. and encouraging me to explore the philosophical side of ship design; and Prof. David Andrews, for the direction during the final stages of the thesis and ensuring the ideas presented in this thesis have strived to meet the rigour required in a Ph.D. They have all provided exemplary guidance during this research. In addition, the supervision, discussion, comments and sense of perspective provided by David Fellows, my second supervisor, through out the course of this Ph.D. has been invaluable.

Secondly, this particular Ph.D. has evolved over a considerable time during which I have had the opportunity to work with a large number of highly skilled engineers, both at UCL and from the wider naval architecture and marine engineering community. The working environment at UCL has allowed me to gain this experience while employed in a full-time role as a member of staff and also provided the flexibility that has allowed the completion of this research part-time. I would like to thank the three Professors of Naval Architecture that have funded me during my time at UCL—John van Griethuysen, Simon Rusling and Paul Wrobel—for both the continued support and the continuing challenges.

I would also like to recognise the friendship and generosity of the researchers and visitors who have called the NAME Research Assistant's office home over the last eight years. They have provided informative discussions on countless topics beyond the scope of this thesis. In particular: Tom Grafton, for the discussions on trimaran roll and introducing me to working in 'research'; Sojan Vasudevan, for the discussions on optimisation and ship design; Tristan Smith, for the discussions on heaving damaged ships and the countless challenging and entertaining debates; Peter Johnson, for the discussions on lifting surfaces and a continued demonstration of entrepreneurial zeal; and CK Tam, for the discussions on completing a thesis.

The environment provided by the other staff and students in UCL's Department of Mechanical Engineering has played an important part in this research, particularly: the students reading for M.Sc. or M.Eng. degrees in either Naval Architecture or Marine Engineering, whose countless questions were always surprising and challenging; and Richard Pawling, Nick Bradbeer and Dominic Burger—researchers working in the Design Research Centre—for the numerous insightful discussions on both ships and ship design.

Finally, I would like to acknowledge the understanding of Manchi, Tom and my parents who have had to share the sacrifices inherent in a part-time Ph.D. without enjoying the excitement that I have experienced along the way.

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Nomenclature

General Nomenclature

AAW	Anti-Air Warfare
AMV	Advanced Marine Vehicle
ANN	Artificial Neural Network
ASuW	Anti-Surface Warfare
ASW	Anti-Submarine Warfare
AVCAT	Aviation fuels
C3I	Command, Control, Communications, and Intelligence
CAD	Computer Aided Design
CEM	Concept Exploration Models
C-K (theory)	Concept-Knowledge theory
CPU	Central Processing Unit
DBB	Design Building Block
DSM	Design Structure Matrix
GA	Genetic Algorithms
GDT	General Design Theory
GDT-REAL	An extension to General Design Theory
LCAC	Landing Craft Air Cushion
LPD(R)	Landing Platform Dock Replacement
LCS	Littoral Combat Ship
MARPOL	International Convention for the Prevention of Pollution From Ships (Marine Pollution)
MoD	Ministry of Defence
PDI	Production–Deduction–Induction
RSM	Response Surface Methodology
RMS	Root Mean Squared
SDE	Ship Design Exercise
SES	Surface Effect Ship
SSC	Ship to Shore Connector
SWATH	Small Waterplane Area Twin Hull
TriSWACH	Trimaran Small Waterplane Area Centre Hull
UCL	University College London
VLCC	Very Large Crude Carrier
VT	Vosper Thornycroft

Naval Architecture Nomenclature

B	Beam
B_{rank}	Bales seakeeping rank
C_B	Block Coefficient
C_M	Midships Coefficient
C_W	Waterplane Coefficient
CPO	Chief Petty Officer
D	Main hull depth
Endur	Endurance
GM	Meta-centric height
GZ	Righting arm
JR	Junior Rating
KG	Vertical centre of gravity
L	Waterline length
P_{10kts}	Power at 10 knots
P_{15kts}	Power at 15 knots
P_{20kts}	Power at 20 knots
P_{25kts}	Power at 25 knots
P_{30kts}	Power at 30 knots
P_{35kts}	Power at 35 knots
P_{40kts}	Power at 40 knots
$PM1$	Prime Mover 1
$PM2$	Prime Mover 2
pow_{avail}	Power available
pow_{req}	Power required
PO	Petty Officer
$Ps_{25\%}$	Prime mover X shaft power at 25% of full power
$Ps_{50\%}$	Prime mover X shaft power at 50% of full power
$Ps_{75\%}$	Prime mover X shaft power at 75% of full power
$Ps_{100\%}$	Prime mover X shaft power at 100% of full power
$sfc_{25\%}$	Prime mover X specific fuel consumption at 25% of full power
$sfc_{50\%}$	Prime mover X specific fuel consumption at 50% of full power
$sfc_{75\%}$	Prime mover X specific fuel consumption at 75% of full power
$sfc_{100\%}$	Prime mover X specific fuel consumption at 100% of full power
T	Draught
vs	Superstructure volume fraction
Vm	Mainhull(s) volume
Vs	Superstructure volume

Δ	Displaced weight
∇	Displaced volume
ρ	Ship density

Functional Group Nomenclature

M_{inf}, M_i	Mass of the Infrastructure functional group option
V_{inf}, V_i	Volume of the Infrastructure functional group option
C_{inf}, C_i	Cost of Infrastructure functional group option
C_{Move}, C_m	Cost of Move functional group option
V_{Move}, V_m	Volume of the Move functional group option
M_{Move}, M_m	Mass of the Move functional group option
C_{Float}, C_f	Cost of Float functional group option
V_{Float}, V_f	Volume of the Float functional group option
M_{Float}, M_f	Mass of the Float functional group option
C_{f+m}	Cost of the combined Float–Move functional group option
V_{f+m}	Volume of the combined Float–Move functional group option
M_{f+m+i}	Mass of the combined Float–Move functional group option
C_{f+m+i}	Cost of the combined Float–Move functional group option
V_{f+m+i}	Volume of the combined Float–Move functional group option
M_{f+m+i}	Mass of the combined Float–Move functional group option

Option and Set Nomenclature

$\mathbf{C}$	Set of combined options
$\mathbf{I}$	Continuous design space
$\mathbf{I}'$	Bounded design space
$\mathbf{I}^{\star}$	Discrete bounded design space
I	Discrete design option or sub-option (also I_1, I_2, etc)
R_F	Float requirements used for the down selection of the options
R_M	Move requirements used for the down selection of the options
R_I	Infrastructure requirements used for the down selection of the options
R_O	Operations requirements used for the down selection of the options
R_S	Ship requirements used for the down selection of the options
S_S	Ship option
$S_{\bar{S}}$	New Ship option
S_{S-O}	Ship option excluding the demands of the Operational items
$S_{\bar{S}-O}$	New Ship option excluding the demands of the Operational items
S_F, F	Float sub-option

$S_{\bar{F}}$	New Float sub-option
S_M, M	Move sub-option
S_I	Infrastructure sub-option
$\mathbf{S_S}$	Set of Ship options
$\mathbf{S_{S-O}}$	Set of Ship options excluding the demands of the Operational items
$\mathbf{S_F}, \mathbf{F}$	Set of Float sub-options
$\mathbf{S_M}, \mathbf{M}$	Set of Move sub-options
$\mathbf{S_I}$	Set of Infrastructure sub-options
$\mathbf{S'_F}, \mathbf{F}_{acc}$	Set of Float sub-options after down selection
$\mathbf{S'_M}, \mathbf{M}_{acc}$	Set of Move sub-options after down selection
$\mathbf{S'_I}$	Set of Infrastructure sub-options after down selection
$\mathbf{S'_{(S-O)}}$	Set of Ship options (excluding the demands of the Operational items) after down selection
$\mathbf{S'_S}$	Set of Ship options (excluding the demands of the Operational items) after down selection

1 Introduction

1.1 Scene Setting

Large marine vessels perform a huge variety of roles in the world's seas and oceans [Colton 2003]. Roles span several broad categories, including: cargo ships[1]; passenger vessels[2]; naval vessels; other self propelled vessels[3]; and barges and other inshore craft. These can be grouped into transport and service vessels based upon significant differences between the vessels operating requirements. Additionally, many candidate options exist for a new vessel's configurations and dimensions [Andrews 1984]. At the initial stages of the design process the designer works to help the customer explore the potential of these possibilities as part of the process of requirement elucidation [Andrews 2003b]. Consequently, the ship designer needs to examine a large and diverse variety of ships during the initial stages of the design process.

Against this backdrop of varied ship types and roles, naval architects have frequently proposed adopting alternative hullforms better suited to a given ship's role than a conventional hullform[4]. Goubault and Allison [2003] describe the range of advanced marine vehicles available and highlight how the strengths and weaknesses of different advanced marine vehicles impact upon their ability to perform different roles. While the conventional monohull hullform is appropriate in the majority of roles, alternative hullforms have demonstrated considerable benefits in certain cases. The benefits of adopting an alternative hullform have been shown to be significant for particular design requirements [Eames 1985]. However, the additional work required to assess these alternative hullforms places a further burden on the designer.

[1] Which can be further subdivided into liquid, dry bulk and general cargo carriers. It can be broadly stated that these three types are either bulk carriers—driven by the weight of the payload—or capacity carriers—driven by the space demands of the payload.

[2] Passenger vessels can be thought of as a type of capacity carrier as the space demands of the passengers generally drives their design. However, a large number of additional systems are required to ensure the passengers are adequately supported.

[3] Typically service ships, such as fishing vessels, offshore service vessel, dredgers and tugs.

[4] Such as the larger number of high speed marine vehicles detailed in the initial 250 pages of [Phillips 1999].

Both industry[5] and government[6] organisations have previously expended significant resources in rapidly determining the most appropriate hullform for a given set of requirements during individual design studies. The level of effort expended in assessing alternative hullforms varies between different ship design programmes. One recent programme which featured an in-depth and expensive—in both time and money—hullform assessment process is described in the following section.

1.1.1 Hullform Selection in the LCS Program

The US Navy's Littoral Combat Ship (LCS) programme explored different hullforms via a multiphase competition that concluded with the building of two different ships intended to allow the US Navy to gain experience of two different hullforms [Long and Johnson 2007]. The best design is intended to form the basis for a class of 65 ships. The LCS programme spent over $500m attempting to select the most appropriate hullform for a ship with a radical concept of operations. The breakdown of the LCS project costs are shown in Table 1.1 from [GlobalSecurity 2006].

Table 1.1: LCS Project Costs, from [GlobalSecurity 2006]

Phase	Funding per Team [$m][a]	No of Teams	Total Cost [$m]
Concept Studies	0.5	6	3.0
Preliminary Design	8.9-10.0	3	28.9
Initial Contracts	46.5-78.8	2	125.3
Shipbuilding Contract[b]	188.2-223.3	2	411.5
Total			568.7

[a]The various competing team were allocated different levels of funding in the later phases of the competition.
[b]A two ship shipbuilding program, tasked with producing the first LCS hulls, one for each hullform.

The initial concept studies stage shown in Table 1.1 featured six industry teams developing designs in parallel against a single set of requirements. Table 1.2 shows additional details on the six team's proposals. It should be noted that the six teams proposed four different hullforms (increasing to five if the deep V monohull and conventional monohull are considered to be distinct).

These six initial designs were down-selected to three designs by the US Navy. The remaining teams—comprising of Lockheed Martin, General Dynamics and Raytheon—

[5]Such as the range of pentamaran designs developed by Nigel Gee Limited and the Izar shipyard [Moret and Gee 2001; Dudson and Gee 2001].
[6]The Triton 97m trimaran demonstrator detailed in [RINA 2004] is an example of two large organisations (the UK Ministry of Defence and the US Department of Defense) expending significant resources to derisk the trimaran hullform for large steel ships.

were then awarded additional funds to further develop each of their designs. These designs are illustrated in Figure 1.1.

Table 1.2: Teams Awarded LCS Concept Studies, from [MarineLog 2003]

Contractor	Hullform	Hull Material
General Dynamics (Bath Iron Works)	Trimaran	Aluminium
Lockheed Martin Surface Systems (Gibbs & Cox)	Deep-V monohull[a]	Aluminium
Northrop Grumman Ship Systems	Monohull	Carbon fibre
Lockheed Martin Marine Systems	SWATH SLICE[b]	Aluminium
Raytheon (John J. McMullen & Associates)	SES[c]	FRP sandwich[d]
Textron Marine & Land Systems	SES	Aluminium

[a] Hard chine monohull hullforms offer substantial benefits at high Froude numbers [Faltinsen 2006]. Consequently they are often studied for small, fast naval ships [Graham 1985].

[b] The Small Waterplane Area Twin Hulled (SWATH) hullform is normally associated with improved seakeeping. However, Lockheed Martin have demonstrated a SWATH derivative hullform—the SLICE—intended to offer resistance advantages. The SLICE hullform is composed of four teardrop-shaped submerged hulls connected to a structural box by short struts. This hullform operates at a high Froude number in the post hump region of the Froude resistance curve which reduces wavemaking resistance. [RINA 2002]

[c] The Surface Effect Ship (SES), or Sidewall Hovercraft, is a partially air supported hullform where two longitudinal buoyant demi-hulls enclose a rectangular air cushion. [Butler 1985]

[d] Fibre Reinforced Polymer (FRP) are composite materials made of a matrix of fibres (e.g. glass or carbon) bonded using a polymer (e.g. epoxy). By adopting a sandwich configuration sectional modulus can be increased compared to a flat panel configuration.

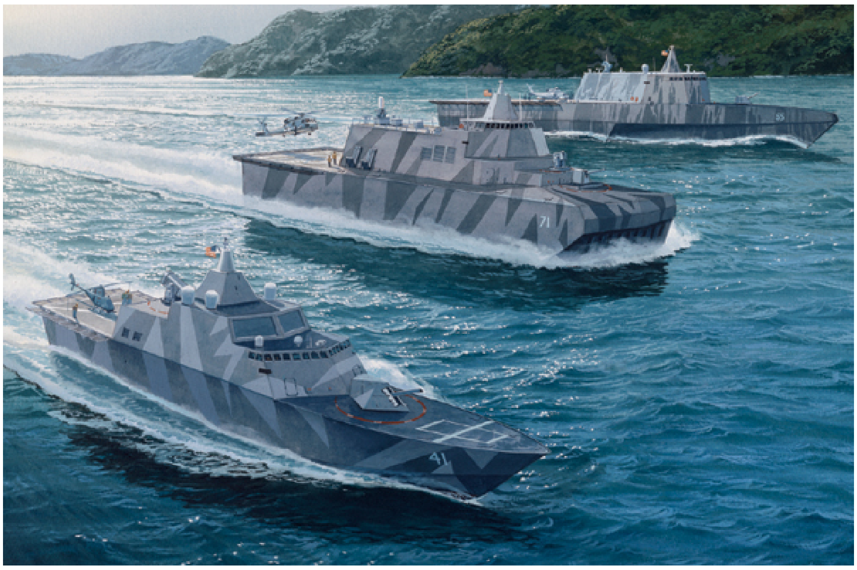


Figure 1.1: US Navy LCS Project's Three Preliminary Designs, showing the Lockheed Martin (front), Raytheon (middle) and General Dynamics (back) proposals, from [US Navy 2005]

Finally the designs were down-selected to a final two solutions which were then built. These final solutions were the Lockheed Martin Deep-V monohull (*USS Freedom* (LCS-1)) and the General Dynamics Trimaran (*USS Independence* (LCS-2)), as illustrated in Figure 1.2.

(a) Lockheed Martin Deep-V monohull [Lockheed Martin 2008] (b) General Dynamics Trimaran [U.S. Navy 2008]

Figure 1.2: US Navy LCS Project Two Final Designs

1.1.2 Defining a Gap

The LCS program expended significant resources on developing an understanding of alternative hullform options as part of the design process. However, the approach taken to develop and explore alternatives came at a considerable expense—both in time and money. In other projects resources to conduct a similar type of competitive evaluation may not be available. In these cases, the decision on hullform type will become an additional task required of the designer. This adds a further layer of complexity to the ship design problem at the phase of the design process where the designer is typically least well informed. Therefore, there is a significant likelihood that alternative options will be excluded prematurely. This could then compromise the achievable performance or cost of the final solution. Some mechanism, which would enable a more cost-effective hullform selection process, would greatly improve exploration early in the ship design process.

This thesis describes an exploration of the task of hullform comparison and selection that occurs in the early stages of the ship design process. A gap in the design methods currently available to the designer was identified. This led to the development of an alternative approach for the hullform selection problem and the new method presented in Chapter 5—a Library Based ship design approach which permits rapid concept design to be undertaken to examine multiple hullform options expediently with, it is claimed, less outlay of resources than the traditional approach.

1.2 Scope

This project is constrained in scope to the early stages of the ship design process and is particularly focused upon the design of naval vessels. A novel design approach suited to resolving the problem of hullform selection is presented and justified. Tools and methods produced during the course of the research described in this thesis have only been developed to a proof of concept level and are therefore not considered suitable for direct use in practical ship design. Only a subset of the available hullforms have been considered in this research, namely monohull, trimaran and catamaran hullforms.

1.3 Research Method

The research project has adopted a research method composed of two elements: an exploratory research element, to structure and identify the problem; and a constructive research element, which develops and demonstrates a solution to the problem. The initial part of the thesis applied an exploratory research method which identified the problem and developed a structure in which a hypothesis could be proposed. Next, a constructive research method was applied to examine this hypothesis through the development of a number of different example design models. The models used different computational approaches to implement a ship design system based upon the proposed approach. The results obtained from these models were then used to inform a discussion of and conclusions on the hypothesis.

The research can be divided into four significant parts:

1. Outline of the Research Issue
2. Hypothesis
3. Implementation, Demonstration and Results
4. Discussion and Conclusions

These are outlined in turn in the following paragraphs.

1.3.1 Outline of the Research Issue

This comprises of a exploration of the published literature on preliminary ship design to identify the issues seen to require research. This investigation has been conducted to provide an understanding of three areas, each of which became a research task and has a specific aim identified for it. The first task was to examine and define the problem of hullform selection in the context of the initial stages of the ship design process. The second task assessed the capability of current ship design approaches and methods to tackle the hullform selection problem. The final task assessed alternative and existing general design approaches with potential to be employed to the hullform selection problem.

1.3.2 Hypothesis

A hypothesis is presented which is considered capable of describing an approach which could assist the designer in exploring the early solution space. The proposed approach, known as a Library Based approach, is described in detail in Chapter 5 together with its underlying methods.

1.3.3 Implementation, Demonstration and Results

Given the hypothesis, two implementations of a ship concept design tool based upon a Library Based approach to ship concept design are presented in Chapters 6 and 7. The first implementation of the Library Based approach explores the decomposition, down-selection and combination steps in the Library Based approach. The second implementation more extensively matches the functionality of the Library Based approach as set out in the hypothesis. This second approach uses advanced computer programming techniques to demonstrate a tool that could be used interactively by a designer engaged in hullform selection.

1.3.4 Discussion and Conclusions

The concluding part of the thesis reviews the proposed Library Based approach in the context of the hullform selection in the early stages of the ship design process.

1.4 Thesis Structure

The four parts of the thesis described in Section 1.3 can be related to individual chapters as follows:

Chapter 2: The Problem of Hullform Selection in Preliminary Ship Design This chapter outlines the key role of the preliminary stages of the ship design process in resolving design problems. An important part of preliminary ship design is considered to be exploration of alternative hullforms as they may offer significant advantages in specific cases and are therefore of interest to the designer.

Chapter 3: Current Ship Concept Design Methods and Implementations The capabilities of current ship design methods to address the problem of hullform selection are critically presented in this chapter. The features of current design approaches are assessed and their limitations discussed. The features that are considered desirable in a ship concept design tool are outlined

Chapter 4: Alternative Approaches from Engineering Design Research The applicability of approaches from the wider field of engineering design research are explored. Key topics that are applicable to the problem of the comparison and selection of alternatives in the initial stages of the design process are highlighted.

Chapter 5: A Library Based Ship Concept Design Approach The conclusions of the previous three chapters are brought together and used to develop a proposal for a Library Based ship concept design approach. This approach is considered suitable for exploring emerging requirements in the very early stages of preliminary ship design.

Chapter 6: An Exploratory Implementation of the Approach The development of an exploratory implementation which demonstrates part of the approach suggested in the preceding chapter is presented. The exploratory implementation has been applied to two cases. Limited conclusions on this first implementation of the Library Based approach lead to the need for something more comprehensive.

Chapter 7: An Improved Implementation of the Approach The improved implementation is presented and it is shown to be both faster to run and more extensively meets the selected requirements identified for the proposed Library Based approach. The decrease in run time is shown by applying the improved implementation to an equivalent design example as the exploratory implementation was previously applied. Following this, an application of the approach to a case with multiple hullform styles is presented.

Chapter 8: Discussion The discussion assesses the proposed Library Based approach given the two example implementations. This discussion takes place in the context of the research issue outlined in an earlier chapter of this thesis.

Chapter 9: Conclusions A set of key conclusions are presented in this closing chapter together with recommendations for potential avenues for further work.

Figure 1.3 outlines the structure of this thesis, highlighting the interrelations between the chapters described above and their place within the four sections of the research method.

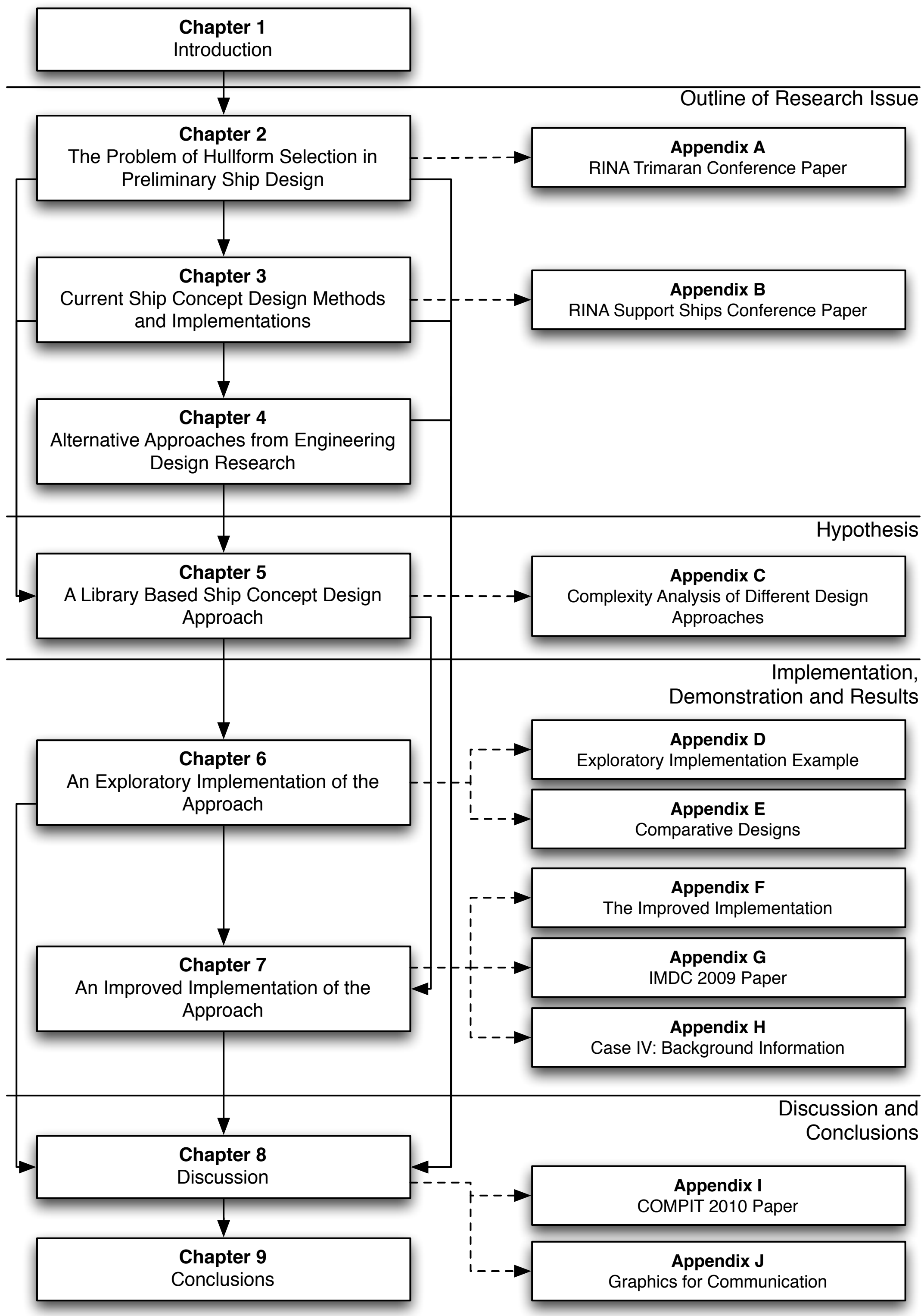


Figure 1.3: Structure of Thesis

2 The Problem of Hullform Selection in Preliminary Ship Design

This chapter presents an overview of the ship design process which outlines the key role of the preliminary stages of the ship design process in resolving design problems. These important preliminary stages are discussed in additional depth. An important part of preliminary ship design is considered to be exploration of alternative hullforms as they may offer significant advantages in specific cases and are therefore of interest to the designer. In this context preliminary ship design matches the description found in [Andrews 1994].

2.1 An Overview of the Ship Design Process

Ships are complex objects with design and construction periods that take many years. [MoD 2005b] provides a description of the management tasks that encompass the design and engineering of a warship[1]. This description highlights nine key levels of maturity in the ship design and construction process:

1. Needs Analysis / Concept Exploration / Key Requirement Identification
2. Concept Definition / Feasibility Design
3. Overall Ship Design
4. Ship Systems Design
5. Detailed Design Integration
6. Ship Test & Acceptance Detailed Planning
7. Ship Assembly / Outfit / Test
8. Post Launch Outfit, Tests and Trials
9. Acceptance Sea Trials

Brown [1996] describes one example of the development process for a naval surface warship which takes approximately four years[2] to proceed from concept exploration (maturity

[1]While similar, the design process for merchant ships differs due to a tightly coupled contracting and financing process. Further information on the merchant ship design and procurement process is available in [Meek 1970; Watson 1998; Eyres 2001; Stopford 2008].

[2]Although numerous examples exist of a more prolonged procurement process.

level 1) to final ministerial approval (maturity level 5) . Understandably, such a design process will be undertaken in a staged manner to satisfy the customer[3] that their needs are being adequately met.

There are many different definitions of the stages of the design process [Rawson and Tupper 2001; Gale 2003; Andrews and Pawling 2008]; however, they follow an analogous structure. The two most commonly described definitions of naval ship design are the British and American Systems, as shown in Table 2.1. Gale [2003] describes the naval ship design process in terms of the US Navy terminology which divides design sequentially into Feasibility, Concept and later phases. In the list shown above and the remainder of this report the equivalent British terminology has been adopted; this uses the sequential breakdown of Concept, Feasibility then subsequent ship design phases.

Table 2.1: Comparison of UK and US Terminology describing Phases in the Ship Design Process

British Terminology	American Terminology[a]	Maturity Levels upon Completion
Concept Phase	Feasibility Phase	Needs Analysis / Concept Exploration / Key Requirement Identification
Feasibility Phase	Concept Phase	Concept Definition / Feasibility Design
Contract Design Phase	Contract Design Phase	Overall Ship Design
System Design Phase	Functional Design Phase	Ship Systems Design
Detailed Design Phase	Product Engineering Phase	Detailed Design Integration

[a] [Gale 2003] also notes that the Contract and Functional Design Phases may be combined to form a System Design Phase. Additionally, the Product Engineering Phase may be separated into Transitional and Zonal Information Preparation Design Phases.

The Concept Phase is concerned with the clarification of requirements and the development of an outline design to meet these requirements [Andrews 1994]. Gale [2003] describes how this is achieved through a series of studies which, in many cases, are developed into a single concept design. This phase clarifies the ship owner's often vague requirements and allows the exploration of the solutions space through a number of studies examining issues such as speed, endurance and cargo capacity. The phase is typified by a systematic exploration process, composed of several cycles of synthesis and analysis, in which options are

[3] This thesis uses the term 'customer' to describe the client organisation(s) with which the designer maintains a dialogue during the design process. In actuality, the customer in a UK warship program is the Secretary of State for Defence who represents a myriad of organisations which may reflect the differing interests of the owner, operator, through life design authority or funding organisations. Understandably, negotiating this array of interested parties, all with potentially differing requirements, increases the complexity of the design process.

explored and the requirements reassessed. Different tasks are undertaken as the Concept Phase progresses, hence this phase is commonly divided into a number of stages [Andrews 1994]. Andrews [1994] also identifies important deliverables of the Concept Phase while recognising that the essence of the Concept Phase is requirement elucidation.

The Feasibility Phase validates the outputs of the Concept Phase. The design is developed to the stage where its performance, cost and risk are understood within all technical areas. Issues are typically explored in a greater depth than in the Concept Phase; e.g. hull proportions and shape would be explored in depth. However, these explorations are only conducted to a level suitable to demonstrate a concept's feasibility [Andrews 1994]. A procurement strategy must be developed to define a construction philosophy in line with industrial capacity. At the same time a through life support strategy is developed. An emphasis is placed on validating and expanding the performance prediction already undertaken to ensure the solution meets the required performance defined in the Concept Phase. Finally, risk areas within the design are explored and minimised where possible[4]. Remaining risk areas are identified and a risk mitigation and management strategy developed for later phases of the design process. A limited overview of this process from the perspective of a shipbuilder is presented in [Stratmann et al. 2006]; although, a critique of this overview highlighting its perceived limited applicability to a specific warship design organisation is presented in [Andrews 2006].

After the Feasibility Phase the Contract Design Phase is undertaken to develop a ship definition suitable for tender by shipbuilders. This phase must confirm the ship's capabilities and costs in order to provide sufficient information for a shipbuilder's bid and define criteria for acceptance after the ship is built. Therefore, the design must be developed to the stage where there is sufficient granularity for the ship to be understood and costed by a shipbuilder and provide the basis for a contract to be placed. This necessitates a more detailed development of the ship to: clarify any minor requirement not yet resolved; finalise any remaining system selections decisions; and, complete development of any remaining specifications and drawings. All to the level required for the shipbuilder to undertake costing. At the completion of this stage the ship design specification will have matured together with sufficient design development of key sub-systems [MoD 2005b].

The System Design Phase is concerned with completing the design of the ship on a system level. All elements of the design are developed to the level where all remaining system level design decisions have been made. [MoD 2005b] describes the outputs of this stage as developing a complete design including sufficient calculations, analysis, modelling and simulation to verify the chosen design at a sub system level. The selected system

[4]Although two major risks areas—cost and timescale—are often beyond the control of the design team managing the Feasibility Phase. These two risk areas are dependant upon both the final build strategy and any concurrent development efforts.

suppliers should also demonstrate that they possess sufficient resources to both complete the production program and carry out any integration tasks.

The complete representation of the ship developed in the System Design Phase is developed in the Detailed Design Phase to ensure producibility. The design information is progressed from a system definition to a block and zone based orientation. A production strategy detailing the order of block construction will be created. These tasks are generally supported by the development of a ‘virtual prototype’[5] which explores the detailed construction issues, in recent years this prototype has taken the form of an integrated product model [Gale 2003]. The virtual prototype developed in the Detailed Design Phase is developed into a collection of small work packages of the order of 200 man hours. The production drawings and diagrams associated with these work packages are then produced. The emphasis of this phase is on providing adequate information to enable the construction of the ship.

Table 2.2 describes the documents and modelling/design tasks undertaken during each phase of the ship design process. Due to the phased nature of the ship design process outputs of the earlier phases strongly direct later work. Therefore, the decisions taken in early phases have the greatest impact upon the overall ship design. As the first phase in the ship design process, the Concept Phase will exert considerable influence on the overall design. However, it is arguably the most resource constrained stage which may limit the number of alternatives which can be explored. The following section discusses this phase in detail to determine the nature of this phase and the influence it exerts on the overall design process.

2.1.1 Concept Phase

The Concept Phase of the ship design process deals with requirements elucidation [Andrews 2003b]. Requirements elucidation addresses the dialogue undertaken to work out and agree the customer’s needs or requirements. This dialogue is achieved through discussions between the customer and the designer informed by design studies. These design studies identify a candidate system via a baseline design and a number of options. The principal deliverable of the Concept Phase are a mature and verifiable user requirements document and an outline system requirement document [MoD 2005b][6]. During the Concept Phase candidate systems are identified via a baseline design and options. These studies also help the assessment of affordability of these solutions and allow the identification of major risks.

These deliverables exert a strong influence on later stages of the design process and hence the final solution. Tibbitts and Keane [1995] provide an assessment of the more significant effects of decisions taken earlier in the design process compared to those made later. Specifically, they provide an estimate that in excess of seventy percent of a ship’s final cost

[5] Either on paper or via a digital model.
[6] Typical products of a warship concept design are listed in Table 5.1 of [Gale 2003]

Table 2.2: Duration, Documentation and Modelling/Design Tasks for each Design Phases, from [MoD 2005b]

Phase[a]	Documents	Modelling/Design
Concept (1-3 years)[b]	Mature and verifiable user requirements document; Outline system requirement document.	Candidate system identified via a baseline design and options.
Feasibility (1-2 years)	Mature and verifiable system requirement document. (Typically 10 drawings[c]).	Defined system concept; Outline general arrangement; Principal standards selection; Preliminary CAD model; Preliminary calculations; Some assessment studies[d].
Contract Design (1-3 years)	Ship design specification mature; Defined integration and test strategy. (Typically 200 drawings[c]).	Validated ship design; Mature and stable architectural design; Key sub-system schematics; Refine CAD model; List of long lead items; Outline safety case.
System Design (1-2 years)	Mature sub-system specification; Defined testing and acceptance strategy. (Typically 3000–30,000 drawings[c]).	Validated sub-system designs and documentation; All sub-system schematics; List of key equipment; refined, mature calculations; All assessment phase studies completed.
Detailed Design (3-6 years)	Mature Integration, testing and acceptance plan.	Production engineering information; Final design review report; Final calculations completed; Final equipment list completed.

[a] An approximate total duration of each phase is given based upon the values found in Figure 1 of [Andrews 1993].

[b] Although individual studies may only be of the order of 20 days. It is difficult to attach a timescale to the concept phase as many large organisations may have an ongoing concept design section [Brown 1996].

[c] Andrews [1993] provides these values for the number of drawings typically developed as the design progresses. Although it should be recognised that types of drawing generated differ as the design process progresses. Furthermore, integrated product models and the earlier outputs of some computer aided ship design systems have increased the speed with which these drawing can be produced.

[d] Assessment studies may include quantitative and qualitative assessment against an existing configuration or given standards.

is determined by the end of the Concept Phase, when only five percent of the total design has been defined. Given the impact of the early stages of the design process, the designer should explore as many options as possible in these stages. If this opportunity to explore the solution space is not taken superior solutions may be missed and the requirement space inadequately explored, with the danger that requirement or cost must be revisited later in the design process.

Andrews [1994] further subdivides the Concept Phase of the design process into three stages:

1. Concept Exploration
2. Concept Studies
3. Concept Design

The first two stages are critical to both exploring the solution space and exploring specific aspects of the solution (by undertaking specific studies). The investigations of certain performance issues undertaken in both Concept Exploration and Concept Studies stages inform the later Concept Design stage. Consequently they strongly shape the remainder of the ship design process and the final design solution that is obtained.

A description of the deliverables provided in the three phases of warship concept design is provided in [Brown 1996] and summarised in Table 2.3 on the following page. There is a clear distinction between the Concept Exploration and Concept Studies elements of the phase in terms of the work undertaken. However, it is difficult to make a clear distinction between the Concept Exploration and Concept Studies in terms of deliverables. Therefore, the outputs of these two elements have been combined together and presented in Table 2.3. The deliverables for the Concept Design stage will only need to be examined to a level necessary to attain approval for Feasibility.

Concept Exploration

Concept Exploration is the first stage undertaken during the ship design process. Concept Exploration refers to the 'unrestrained exploration' of the broad outline of the vessel [Andrews 1994]. During Concept Exploration the designer is interested in considering all possible options to determine the region of the solution space that the eventual solution is likely to inhabit. The approach should be exploratory and divergent, allowing the designer to consider radical alternatives that would satisfy the requirements in novel ways and offer performance advantages. During this stage three design parameters are suggested by Andrews [1994] as being of primary interest to the designer undertaking a warship design. These are shown in Table 2.4 on page 37.

This exploration is described in [Pahl and Beitz 1984] as an 'abstraction phase' which is necessary to identify the essential parts of any design problem. However, Pahl and Beitz

Table 2.3: Deliverables within the Concept Phase for a Naval Combatant, from [Brown 1996]

Concept Exploration & Concept Studies	Concept Design
• Clearly understood roles, evolving into technical requirements • List of acceptable technical solutions and record of why others were rejected • Availability of skills and resources to develop the preferred solution • Definition, in general terms, of the relative importance of different topics • Consideration of the impact of ship life, refit and operational patterns on the design • Broad manning philosophy • Commitment and understanding of all concerned • Identification of limits and constraints • Risks to ship and programme • All necessary data assembled • Explore likely drivers, including: • Concept Exploration – Packaging – Capability – Technology • Concept Studies (typically ship related issues) – Speed – Seakeeping – Endurance – Style – Signatures – Survivability – Complement – Others (e.g. ASW, AAW, ASuW etc.)	• Fighting – Weapons, Sensors and C3I – All equipment items and locations, together with a comprehensive assessment of the payload's impact upon the ship – Aircraft – Hangar and Flight Deck arrangement, internal demands such as AVCAT – Susceptibility – Signature requirements relating to propulsor, thermal signature, radar cross section, and other significant signatures. – Vulnerability – Including zoning philosophy together with shock, blast and splinter assessment • Moving – Machinery – Number and type of prime movers and transmission system – Auxiliaries – Assessment of electrical load and generator sizing – Systems – Policy on system runs – Hydrodynamics – Principal hullform characteristics, estimates of resistance and motions of the hullform – Endurance – Definition of cruising speed and assessment of range with sizing of fuel tanks – Seamanship – Anchor siting, replenishment point and routes, views from bridge etc. • Architecture – Stability – GM, GZ and serious damage cases – Margins – Clear policy – Weights and KG – Estimate to reasonable accuracy (5%) – Strength – Illustration of structural continuity – Materials – Hull material and maintenance policy for ship life – Standards – Definition of applicable standards • Living – Broad space allocation with consideration of passageway routing • Operating – development of overall availability, reliability and maintainability policy

Table 2.4: Primary Warship Design Parameters, from [Andrews 1994]

Parameters	Example
Packaging	Gross vessel size, e.g. Mini / Current Concept / Enhanced Concept
Capability	Convention Payload vs. Reduced Payload
Technology	Convention Monohull vs. SWATH / Trimaran

[1984] focus on product design, where an abstraction phase is easier to implement as key requirements could be identified before the outset of the design process; an abstraction phase is less applicable to the design of highly complex large items[7], such as ships, where requirements elucidation takes a key role in the Concept Phase.

Mistree et al. [1990] use a structured decision support process to explore the development of design concepts as the designer moves through a design process. Mistree et al. highlights the different steps a concept experiences as it is developed through the concept design process. In particular, the authors draw attention to the divergent–convergent nature of the design process. During divergent steps the variety of concept designs being explored increases. During convergent steps unacceptable concepts are discarded while the beneficial features of partially acceptable concepts are selected and combined to form new options. These divergent and convergent steps are a key feature of concept exploration. While the decision support process proposed by Mistree et al. is useful in analysing work undertaken in the concept phase of a design process, it is unclear if the proposed methods could usefully assist a designer in developing radical concepts during concept exploration.

Concept Studies

Concept Studies attempts to bring focus to the likely solutions developed in the exploratory and divergent Concept Exploration phase. The Concept Studies phase examines significant design issues to inform the synthesis[8] of the baseline and certain tradeoff studies. Andrews [1994] suggests further issues, which may be of interest in the Concept Studies phase, these are shown in Table 2.5. Many of these particular design drivers are also present within merchant ships.

Concept Design

The Concept Design stage is the major stage in the preliminary design of ships. The Concept Design stage takes the conclusions of the Concept Exploration and Concept Studies

[7] Suh [2001] provides a definition for large systems related to their complexity; ships conform to this definition.

[8] synthesise, to make a synthesis of; to put together or combine into a complex whole; to make up by combination of parts or elements. [Oxford University Press 2006]

Table 2.5: Secondary Warship Design Issues, from [Andrews 1994]

Driver	Example
Speed	Fleet speed
Seakeeping	Helicopter operations
Endurance	Pacific ocean transit
Signatures	Low machinery and propeller noise
Survivability	Three compartment standard
Complement	Crewing philosophy
Logistical considerations	Integrated logistic support
Margins philosophy	Growth, design and Board margins[a]
Robustness	Plating corrosion margin
Adaptability	Space provided to enable future modification to both ship and role
Standards	Applicable standards used in design (e.g. Lloyd's Naval Ship Rules)

[a] The standard practise employed within UK warship design divides the overall ship's margins into three elements: The growth margin, which accounts for items such as accumulated paint and personal items. The design margin, a contingency which accounts for uncertainty problems in the design process. The Board margin, which is an allowance for additional equipment that the owner will decide needs to be fitted later in the ship's life.

stages and develops a baseline design of the likely option(s) emerging from Concept Exploration and informed by Concept Studies. The systematic variation of the design around the baseline point allows the designer to explore the cost and benefit of the options to better inform the customer. The baseline design and options developed in this stage possess sufficient detail to allow the designer to perform the four following tasks:

- to sufficiently define the baseline with which to demonstrate the design tradeoffs;
- to adequately cost the design for it to be evaluated in any required approval process (i.e. Initial Gate Approval in UK Ministry of Defence);
- to adequately define and justify the associated requirement;
- to enable Feasibility to commence (it may also suggest likely design drivers that Feasibility needs to focus on as well as verify the design's viability).

If these four tasks are completed and approval is given the design can proceed to the next stage of the design process—Feasibility.

2.1.2 Conclusions on the Ship Design Process

It is apparent that the Concept Phase of the ship design process forms a key element in the design process. If the designer is to fully explore the potential benefit of alternative options then the adopted design process must facilitate the examination of these different options within the Concept Phase. In particular, the Concept Exploration and Concept Studies stages present a valuable opportunity for the designer to examine alternative options; useful design knowledge gained here will have a profound impact on the rest of the ship design process. However, these stages of the design process contain significant difficulties that complicate design tasks. These difficulties are discussed in the following section.

2.2 The Difficulties of Ship Concept Design

In the previous section, the Concept Phase of the ship design process was outlined as forming a key initial step in the overall process. This phase is particularly challenging due to the complex decision making environment it encompasses. Erikstad [1996] outlines this preliminary ship design 'task environment'—the external characteristics of the design problem—which form the backdrop to the designer's decision making within this stage of the design process. The task environment is described through the following seven 'invariant' characteristics—setting the limits which Erikstad states must be considered when choosing a problem solving strategy for a given design task:

- "Complex mapping between form and function;
- Multi-dimensional, partly non-monetary performance evaluation;
- High cost[9] of error;
- Shallow knowledge structure;
- Strong domain tradition;
- Strict time and resource constraints on the design process;
- Predominantly 'one-of-a-kind' and 'engineering-to-order' solutions."

These 'invariant' characteristics are common across many different design fields. However, the design and build process of large marine systems contains an additional constraint which amplifies its difficulty: the lack of a prototype phase after Feasibility. Various authors have discussed the impact of no prototype phase in the context of the design of large, complex systems [Andrews 1998; van Griethuysen 2000]. The lack of a full scale prototype presents a fundamental problem in the design process and is closely coupled to a number of the characteristics listed above.

[9] In this context Erikstad [1996] includes costs in money, time, manpower and other resources.

Erikstad's seven 'invariant' characteristics can be recast as two issues which result in additional complexity in the ship design compared to the design of most other[10] regularly produced products:

- Complexity of ships;
- Complexity of ship design.

These issues are discussed in Sections 2.2.1 and 2.2.2.

2.2.1 Complexity of Ships

It has been argued that ships are one of the most complex products produced by mankind on a regular basis[11]. Table 2.6 demonstrates that ships—particularly large naval vessels and other complex service ships—are up to an order of magnitude more complex than comparable, regularly produced, engineering systems (all of which have several prototypes before design for manufacture commences) [Lamb 2003].

Table 2.6: Number of Unique Parts in Product, from [Lamb 2003]

Product Type	Number of Unique Parts
Aircraft Carrier	2,500,000
Submarine	1,000,000
VLCC	250,000
Boeing 777	100,000
Fighter aircraft	15,000
Automobile	1,000

The Concept Phase of the ship design process is made more difficult due to interdependencies which occur within the ship itself (e.g. such as the circular relationship between the dimensions of a ship's hullform and the propulsion machinery that it both requires and is able to support). Additionally, analysis limits arise from the limited experimental and analytical knowledge base within many aspects of marine systems (e.g. the limited full scale performance data available for some hullforms such as the impossibility of testing the structure on a '100 year wave'). This has a substantial impact upon the design of marine vehicles due to the difficulties it introduces in predicting operating characteristics

[10] The other field of engineering design without a full scale prototype tested before production is that of civil engineering products such as bridges and dams (and possibly also large buildings, such as concert halls). Ships are unique in the set of vehicles in this regard.

[11] Especially if a challenging payload—such as a concurrently developed combat system—must be integrated. Gates and Rusling [1982] provide the following quote from Cdr C. Graham, USN: "Today's warships are the most complex, diverse and highly integrated of any engineering system".

at the air-water interface [Erikstad 1996; Bertram 2000]. The complex, largely non-linear behaviour that occurs at the air-water interface is difficult to predict, especially when probabilistic, long-term characteristics are being assessed[12].

Three of the 'invariant' characteristics described by Erikstad [1996] are closely linked to the complexity of ships and will be discussed in the remainder of this section:

- "Complex mapping between form and function;
- Shallow knowledge structure;
- Strong domain tradition."

Complex mapping between form and function

Erikstad [1996] describes the complex mapping of form and function that occurs within a ship. While other engineered object are multi-functional, the unique challenges inherent from operating on the sea surface lead to difficulties linking form and function in any solution. For example, the ship's hull is a multi-functional component that, among other capabilities, provides both strength and buoyancy while attempting to minimise both resistance and motions. Erikstad [1996] provides an example of the relationship between form (in terms of the vessel's physical description) and function (in terms of the ship's performance) which is shown in Table 2.7. He comments on the difference between most computer systems, which rely upon a (form)→(function) mapping, in contrast with the design process, which he describes as a (function)→(form) mapping[13]. Although Andrews [1986] highlights the importance of an initial decision on style to break into any mapping between form and function giving (function)$\xrightarrow{\text{style choice}}$(form).

Table 2.7: Some Relations between Form and Function, after [Erikstad 1996]

(form)		(function)
(hullform & propeller)	→	(required SHP)
(hullform)	→	(seakeeping behaviour)
(hullform, propeller, machinery)	→	(ship speed)
(hullform and all other ship systems)	→	(total cost)

[12] In this case the lack of a prototypes stage where this assessment is undertaken is apparent, especially if ship building is compared to the automotive or aero-space industries where issues such as fatigue and other failure mechanisms are examined through testing prototypes to destruction. Occasionally prototypes are developed in the marine field (e.g. Triton which acted as a 2/3 scale destroyer structural prototype. However, it should be noted that this was not tested to destruction [RINA 2004]).

[13] Andrews questions the legitimacy of this mapping; a discussion of his comments can be found in Section 2.2.2.

From a design perspective many aspects of ships give rise to open problems driven by soft knowledge [Erikstad 1996]. As a consequence, a preference for adopting well understood designs exists within the ship building community. This approach presents a substantial problem for a designer proposing an innovative or revolutionary design. This is further complicated by the numerous links between the form of particular element of the solution and the functions it must perform or capabilities it must possess.

Shallow knowledge structure

Gale [2003] identifies the concept of 'degrees of uniqueness' to separate novel and well understood designs. Andrews [1998] identifies different types of design, depending upon the knowledge available[14]. 'Degrees of uniqueness' result in simple evolutionary design being classified as a well understood design problem that allows the designer to draw upon large stores of data. These data stores simplify the design process and mitigate some design risk. In contrast, the most challenging type of design—revolutionary design—occurs when novel solutions are pursued. Exemplars are Advanced Marine Vehicles (AMV) such as the Surface Effect Ship (SES). In the 1960s the SES was viewed as a potentially viable solution for a perceived demand for fast naval craft by the US Navy. Over $400 million[15] was spent from the late 1960s to 1979 upon an extensive research and development program before the technology was felt to be sufficiently derisked [Clark et al. 2004].[16]

Different 'degrees of uniqueness' give rise to specific problems in relation to performance prediction tools. During the design of a ship the designer must rely upon the application of performance prediction tools. These tools are limited in the range of their applicability. Some, such as stability analysis tools, may be flexible and able to successfully model a range of ship types. Other tools, such as resistance series[17], are constrained to a range dictated by the data or assumptions upon which the tool is based. If a revolutionary design is examined, the designer has to revisit these assumptions to ensure the predictions are valid, this may involve instigating an appropriate research and development programme (as in the case of the US SES [Clark et al. 2004] and UK Trimaran programme [RINA 2004]).

[14] Andrews [1986] provides a discussion on the types of ship design which explores the ship design methods, this is discussed more comprehensively in Section 3.1.

[15] This cost figure is taken from [Clark et al. 2004]; Other authors have suggested a higher overall cost for the SES research and development program [Andrews 1986].

[16] At this point the programme had advanced to the stage where the US Navy's technical knowledge was sufficient to build a 3000 tonne demonstrator. However, the program was abandoned weeks before construction commenced due to a lack of a perceived mission [Clark et al. 2004]. This could be viewed as a classic example of the dangers of not fully understanding the requirements as discussed in Section 2.2.2.

[17] e.g. Series 64, and Holtrop [Yeh 1965; Holtrop 1984].

Strong Domain Tradition

Erikstad [1996] gives an example of the domain tradition within the marine field through a comparison of the documentation required for the design and production of a merchant ship and a fixed offshore installation[18]. Such domain tradition masks complexity to a large degree, since it exploits a common understanding between involved parties. One consequence of the strong domain tradition is the difficulty of presenting and communicating novel options, such as an alternative hullform, in a manner familiar to the interested parties. As a result, the domain tradition is antipathetic to novel solutions.

Two other invariant characteristics—the high cost implications of design errors and the strong time and resource constraints on the design process, both discussed below in Section 2.2.2—also contribute to a strong domain tradition within ship design.

2.2.2 Complexity of Ship Design

Beyond the complexities apparent within ships themselves there are also a number of complexities which emerge from the ship design process itself. These are a consequence of the significant constraints that arise in undertaking the ship design process together with a ship's inherent characteristics as physically large mobile systems. Andrews [1981] describes, with examples, three categories of constraints within the ship design process:

- Direct constraints on the design—often spelt out in requirements;
- Constraints on the design process—concerned with practices in a given design organisation;
- Constraints originating from the design environment—often originating with government or commercial policy.

Precise constraints will differ between design projects, however parallels exist between these categories of constrains and four of the 'invariant' characteristics described in [Erikstad 1996]:

- "Predominantly 'one-of-a-kind' and 'engineering-to-order' solutions;
- Multi-dimensional, partly non-monetary performance evaluation;
- High cost of error;
- Strict time and resource constraints on the design process."

These can be attributed to the complexity of ship design.

[18] The merchant ship would require 20-50 kg of documentation to satisfy government and class, while the installation would need 30-50 tons. He attributes the difference to a historic tradition that has resulted in the interested parties having a similar anticipation of the design artefact.

Predominantly 'one-of-a-kind' and 'engineering-to-order' solutions

Rittel and Webber [1984] describe certain types of design as a 'one-shot operations' with no opportunity to learn by trial-and-error. This can be seen to be true for ship design. Many ships are essentially one-of-a-kind objects when constructed and almost all have no full scale prototype. This statement may be questioned for the case of large batch or family construction where some opportunity for redesign may occur. However, given the timescales involved in the shipbuilding process, redesign may not occur in time to impact upon the build of immediately subsequent ships in the class. Furthermore, changes will come at a significant cost. The one-of-a-kind nature of the ship design process can inhibit the designer from reusing substantial parts of previous design knowledge.

Multi-dimensional, partly non-monetary performance evaluation

The procurement of ships, particularly naval vessels, relies upon the evaluation of a large number of non-monetary performance characteristics that are hard to evaluate together. Thus evaluation of these characteristics is difficult to automate, so the designer's or customer's judgement must play a key role in the design process.

High Cost of Error

The impact of complexity within a large engineering system is discussed in [Eckert et al. 2004]. Although Eckert et al's work is based upon rotary-wing aircraft, the issues discussed are applicable to complex marine vehicles. The impact of changes to a design are explained in terms of the extent of the downstream effects caused by the propagation of design changes. Eckert et al. show that the level of complexity and interconnections within any design increases these downstream effects. This is very applicable to ships and the ship design process. The additional levels of complexity which applies to products in the marine field, as shown in Table 2.6, amplify the difficulties of propagating design decisions downstream through a design.

Design processes revolve around moving from a position of minimal knowledge of the solution, via the gradual definition of greater levels of design detail, to a position where the system is well understood and can be constructed. This process is illustrated in Figure 2.1, from [Gale 2003].

As the level of detail within a design increases, and complex interactions can be evaluated, the inherent risk within the design reduces. Unfortunately, this increase in detail causes an increase in the time required to implement and propagate changes through the design. There have been attempts to address the dichotomy within design between risk and knowledge, by considering the form of design detail [Mierzwicki 2003; Brown and Mierzwicki 2004]. Figure 2.2 demonstrates the trade-off between the risk inherent within

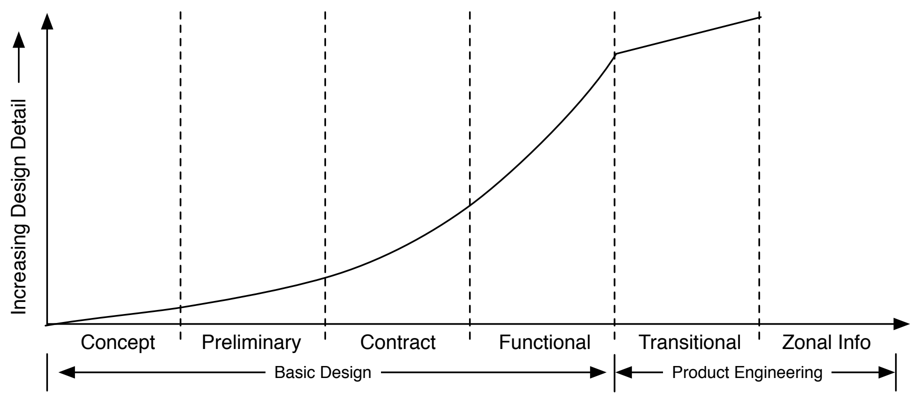


Figure 2.1: Detail in the Ship Design Process, after [Gale 2003]

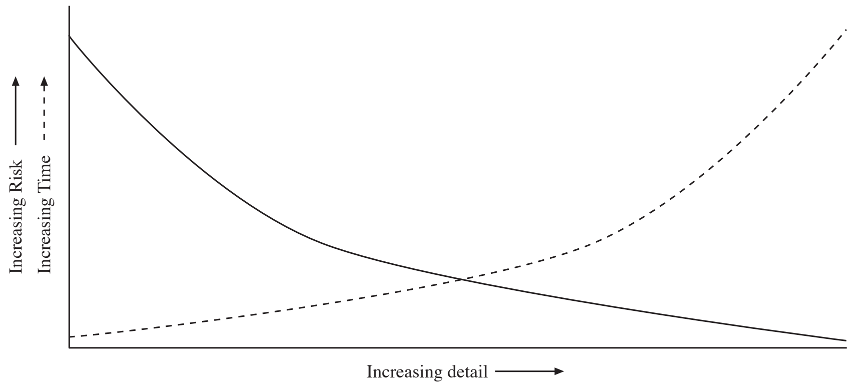


Figure 2.2: Impact of Increased Granularity

a design and the time required to implement changes to the design, as described in [Eckert et al. 2004].

The high cost of error is seen to be a function of a ship's complexity. Complexity results in extensive resources being required to propagate changes through the design when they inevitably occur. The designer manages the issue of complexity, through adopting simplified models of the ship. As the design progresses, these models must be developed and improved to ensure they are sufficiently detailed to construct the ship while ensuring the ship continues to meet its performance requirements [Heather 1993a]. This development process is critical, as the lack of a prototype within the ship design process places the emphasis on the designer to get the design right first time. This often leads to the designer minimising any design risk and discarding a potentially better solution too early in the design process.

Strict time and resource constraints on the design process

Challenging procurement timescales, in both merchant and naval shipbuilding[19], give rise to a large number of design tasks that need to be performed. Decisions are usually made before a comprehensive understanding of the problem has been formed.[20]

2.2.3 Conclusions on the Difficulties of Ship Concept Design

Any ship concept design method must be able to address both the inherent complexity of the completed ship and the complexity of the design process. However, the level of detail for a design developed during the concept design stage of the ship design process is likely to be insufficient to directly address the issues of complexity and full performance prediction. Given this constraint there is still a pressing need to explore alternatives during the Concept Phase of the design process as part of the process of requirement elucidation outlined in Section 2.1.1. The next section examines the role of requirements play in the ship concept design process.

2.3 Requirements in the Ship Concept Design Process

The customer's needs are usually key to initiating the concept design process. One of the designer's primary concerns is to properly understand these needs and the likely requirements that arise from them. However, it is important to note that the designer must also ensure that constraints originating from other participants in the design process are recognised, questioned and then agreed with the requirements owner following a proper concept elucidation process [Andrews 2003b]. Three levels of constraints occurring within the ship design process stated in Section 2.2.2 are only part of the influences on the design process, the designer's 'idiosyncratic' stamp—the influence the designer has upon the design, brought about by his/her value structure, in combination with the designer's linguistic, visual and value schemas [Andrews 1998]—is a further important factor in the design process. Both the constraints and the designer's idiosyncratic stamp are integral to requirement elucidation.

[19] While the concept design stage of naval shipbuilding may have less challenging timescales, excluding the particular challenges of meeting externally enforced political milestones, the build process for a naval ship is as time limited as that of a commercial ship, although it is usually of a much longer duration. This additional time is a result of the complexity of both the vessel and the normally complex, developing payload requiring integration.

[20] This decision is further complicated for naval ships by the political and bureaucratic process in which the ship design takes place: "[Naval ship design is a] multi disciplinary, multi-million dollar Navy extravaganza where every decision must be analysed, traded off, massaged and documented to the point that the basic design issues are often lost in the process." [Benford 1979]

2.3.1 The Requirement Set Employed within the Ship Design Process

Taking the requirement owner's needs as the start of a dialogue leads to a design and a set of requirements. It is useful to outline the types of requirement that are likely to emerge. As requirements differ between design projects it is difficult to find a comprehensive list. However, a set of possible issues, relevant in warship design[21], that give rise to possible requirements is presented in [Lloyds 1988]:

- Speed, Power and Endurance;
- Space, Layout and Weight;
- Structural Design;
- Intact and Damaged Stability;
- Seakeeping;
- Manoeuvrability;
- Military/Commercial Features;
- Construction Costs and Build Time;
- Through Life Costs.

Brown and Andrews [1980] highlight the subset of these concerns that form the five key naval architecture concerns critical to ensuring the performance of the design, namely: Speed, Strength, Seakeeping, Stability and Style. These five areas—which Brown and Andrews termed S^5—provide a generic overview of both the requirements that must be satisfied and the standards that must be met to ensure the ship is suitable for its operating environment from a naval architecture perspective.[22] Speed, Strength, Seakeeping and Stability are the traditional technical areas that form the engineering sciences applicable to naval architecture. Style refers to the overall characteristics possessed by a design. This includes the ship's broad characteristics, such as configuration, robust structure, margins, signatures and zero emissions, as well as the aspects of the design defined by the '-ilities' (also called transversals by some authors [MoD 2005b]).[23]

[21] Note that this list contains those issues—assessed during the inquiry into the 'short-fat ship'—are those that are of especially relevant to the choice of hullform style.

[22] In this context operating environment refers to both the economic/political and physical environment that a ship must operate in [Andrews 1981; Meadows and Meadows 2003; Colton 2003].

[23] Andrews [1998] list of the key '-ilities' is reproduced below:

Authors have presented a wide variety of design drivers that have emerged during ship design projects:

Auxiliary Oiler: In a naval axillary vessel, such as the fleet tanker detailed in [Cooper et al. 2007], the stability requirements implied by the current standards proved challenging to fulfil particularly since other challenging regulations were introduced in this instance, such as the MARPOL double hull tanker regulations [International Maritime Organization 1992].

Type 23 Frigate: The significant acoustic signature requirements of the Type 23 frigate originate from its key anti-submarine warfare mission using a towed array sonar system. The desire to obtain significant reductions in the ship's signatures drove the adoption of a novel combined diesel electric and gas turbine machinery fit [Easton 1987].

Landing Platform Dock Replacement: During the concept design of replacement vessels for the UK amphibious fleet presented in [Dolton and Silvia 1986] four key design drivers are highlighted: Logistics handling; Propulsion; Packaged weapons and command/control/communications equipment; and Landing craft. In particular, the authors drew attention to the key importance of the vessel's landing craft in maximising the rate at which vehicles are offloaded, leading to the adoption of Ro-Ro Landing Craft as part of the LPD(R) project.

In many cases the S^5 performance aspects may relate customer requirements to some of the design issues identified above (and in Section 2.1.1). In other cases the emergent design drivers may not originate directly from the customer requirements. Instead, while the designer is developing a design able to satisfy the requirement owner's needs other issues, such as stability and strength, may emerge as drivers during the design process. In this case they are a consequence of the actions and decisions taken by the designer in developing a 'balanced' engineering solution. Andrews demonstrates in Section 2.7 of [Andrews 1984] that the needs which are commonly presented by a customer are insufficient to form the complete design requirements. Hence, one of the designer's roles is to obtain the requirement owner's agreement to appropriate standards necessary to develop a workable solution. [Andrews 1984] suggests design standards—the performance intended to be

- reliability
- availability
- maintainability
- manability (human factors)
- function
- producibility
- supportability
- feasibility
- social acceptability

There are other '-ilities' which may be applicable to certain ships (i.e. survivability), therefore the list above is only partial.

Andrews notes that many of these issues have only recently been discussed in a formal engineering context.

achieved, typically described by codes of practise, methods of manufacture and assembly, safety standards and design procedures—as a means of providing an appropriate additional input to a ship synthesis process. However, design standards only form part of the input to a ship synthesis process, the designer must also develop a set of requirements that are determined through dialogue with the customer on their needs. This set of requirements is developed through a process of requirement elucidation.

2.3.2 Requirement Elucidation

A second role the designer must adopt is ensuring the customer is made aware of the significance of all the likely requirements upon any emergent design [Rawson and Tupper 2001]:

> "The earliest stages are typically a debate with the owner, proposing various ways in which the owner's wishes could be fulfilled, matching the operations envisaged to the investment that would be necessary to perform them."

Andrews [2003b] identified this key process as being requirement elucidation, which should drive the concept phase of the ship design process. The process of elucidating the design requirements can only be achieved through design. It is also important to recognise that any limitations of the designer's adopted design method or tools may well constrain the exploration by failing to consider alternative options and hence limit a thorough exploration and elucidation of the customer's true needs.

2.3.3 Ship Concept Design as a Wicked Problem

As discussed in Section 2.1.1 one of the principal aims within the Concept Phase of the ship design process is the elucidation of the requirements. This is necessary due to the circular relationship between the requirements and the solution. This relationship has been called a 'Wicked Problem' [Andrews 1981]. Andrews states that the ship design process shares many characteristics with other wicked problems. Common characteristics apply to both these other wicked problems and the Concept Phase of the ship design process. The ten characteristics used by Rittel and Webber [1984] in identifying the issue of wicked problems in the domain of urban planning are listed below:

- "Every wicked problem is essentially unique;
- Every wicked problem can be considered to be a symptom of another problem[24];

[24] A wicked problem can be considered to be a symptom of higher level problems; higher level problems are broader and more difficult to resolve. Attempts to resolve lower level problems, the symptoms, are ineffective, however higher level problems are difficult for most organisations to resolve.

- There is no definitive formulation of a wicked problem[25];
- Wicked problems have no 'stopping rule'[26];
- Solutions to wicked problems are not true-or-false, but good or bad;
- There is no immediate and no ultimate test of a solution to a wicked problem;
- Every solution to a wicked problem is a 'one-shot operation'; because there is no opportunity to learn by trial-and-error, every attempt counts significantly;
- Wicked problems do not have an enumerable (or an exhaustively describable) set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan;
- The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem's resolution;
- The [designer] has no right to be wrong."

Within UK Defence related shipbuilding this issue has been exacerbated since the introduction of SMART Procurement [MoD 2005a] by the requirement to separate the definition of requirements and the production of technical solutions. Hambleton et al. [2005] describe the definition of a Systems Requirement Document as 'describing the required system behaviour without prescribing a technical solution'.[27]

2.3.4 Non-Compliant Requirements and Satisficing

Once a baseline design is developed the impact different requirements have upon the design can be examined. At this stage any conflicts or non-compliances between the different re-

[25] Wicked problems are not amenable to an exhaustive formulation. Rittel and Webber [1984] state that the information needed to understand the problem depends upon the designer's method of solution; Suh [2001] supports this description in his definition of large, complex systems.

[26] Rittel and Webber [1984] describe the 'no stopping rule' as the absence of a clear point at which the solution to a wicked problem is achieved, there is always more work which can be undertaken.

[27] Many commentators have questioned the wisdom of this approach, highlighting that while it may work for a software system (such as a combat management system) it is inappropriate for a physical system (such as a ship); Andrews [2003b] questions this from the perspective of the experienced naval ship designer and finds support from his position from the Professor of Systems Engineering at the Royal Military College of Science [John 2002] (as summarised in [Andrews 2003b]):

- "Not to produce requirements without thinking of a material solution and to avoid jumping to one solution;
- Alternative material solutions have to be considered to properly undertake requirements elucidation, if the appropriate requirements and constraints are to be found;
- All solutions being explored are conditional and an approach of 'so IF then that...' should be adopted".

Suh [2001] provides a description of the design process in general which justifies the action of stepping between the solution and problem space.

quirements will emerge. Non-compliance requires the designer to either re-design or consult with the customer to redefine and relax their requirements. Requirement relaxation relates to how much flexibility the customer is willing to allocate to the different requirements. It is a critical process where the requirements are traded off against each other to develop a solution which is well balanced between the different requirements.

Erikstad [1996] describes the preliminary ship design as a ‘satisficing’[28] process. Satisficing attempts to develop a compromise solution through degrading certain performance characteristics until a ‘good enough’ solution is achieved. This process is most commonly observed through reduction in technical performance to satisfy a cost target, however this process entails trade-offs between different performance areas. Therefore, satisficing can be viewed as an appropriate term to describe the trade-off process which occurs at the early stage of the ship design process (in UK naval ship design this occurs prior to Initial Gate at the end of the Concept Phase before the Feasibility Phase).

Various methods exist to facilitate the comparison of options as part of the satisficing process such as Multi Attribute Value Theory [Sen 1991; Brown and Thomas 1998; Barone and Bertorello 2004]. However, these methods make the fundamental assumption that a valid solution exists for the requirement set. Satisficing provides a solution for the case where requirements are strongly non-compliant.

This case can be demonstrated by representing the solution space in a parametric fashion. Figure 2.3 shows a graphical representation of a solution space with three regions containing the solutions which satisfy requirements for Payload, Speed and Range. The overlapping parts of the regions contain solutions that meet multiple requirements.

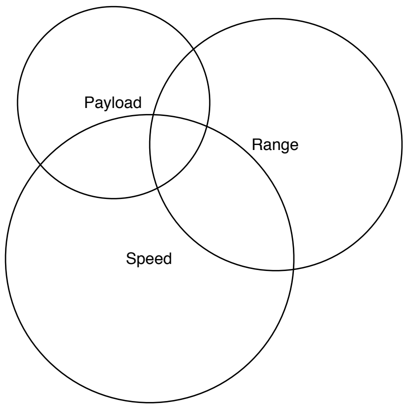


Figure 2.3: Parametric Solution Space, after [Burcher and Rydill 1994]

Figure 2.4 presents a development of Figure 2.3 with an additional draught requirement introduced. In this case some overlap exists between the new draught requirement and the

[28]Or satisfice; a term due to Simon [1981].

original requirement set. However, the solution space shown in Figure 2.4 fails to provide solutions which meet all four performance requirements.

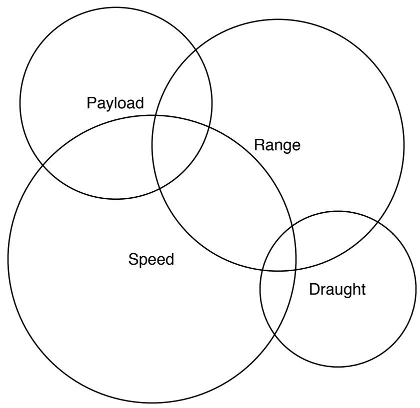
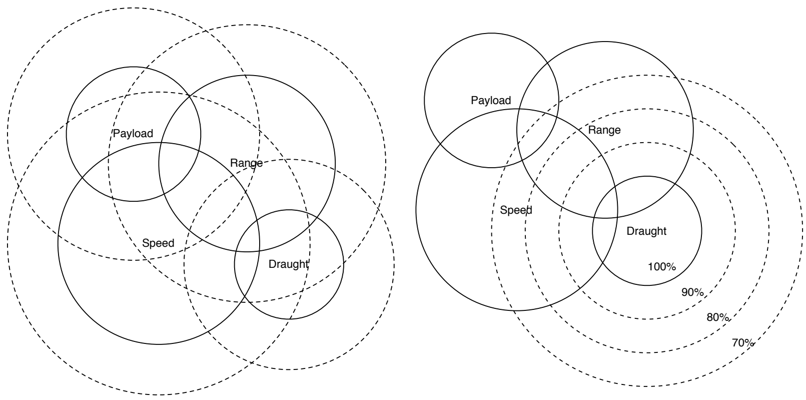


Figure 2.4: Improved Parametric Solution Space with Additional Non-compliant Requirement

Two possible methods for producing a viable solution by reducing the performance requirement are shown in Figure 2.5. Figure 2.5a shows the case where all four requirements are relaxed. Figure 2.5b demonstrates the effect of relaxing a single requirement. These figures are purely illustrative.



(a) Four Requirement Relaxed (b) Single Requirement Relaxed

Figure 2.5: Parametric Solution Space Indicating the Effect of a Relaxation in the Performance Requirements

The impact of the relaxation of a requirement is important for finding an appropriate solution. This is especially true for the Concept Phase of the ship design process. [Maher and Tang 2003] provides commentary on the interplay between the problem and solution space within the concept design process.

It is not normally the responsibility of the designer to determine the requirements during the ship design process. Therefore, any change to the requirements must be discussed and confirmed with the customer. This interplay between the customer and designer is addressed in [Andrews 1991]:

> "The essence of concept design is divergence and innovation in trying to ascertain what is in the customer's real requirement and how that can be tuned to what is technically realistic and affordable."

Andrews [2003b] discusses this issue in more depth, with specific reference to requirement elucidation within the acquisition process of naval ships.

2.3.5 Impact of Requirements upon the Ship Solution

The previous sections have discussed the role of requirement elucidation as part of the design process. This section builds on that, exploring the impact of requirements upon the ship itself.

Various authors have described how altering the requirements radically alters the characteristics of the ship solution. Section 2.2.1 highlighted the apparent complexity of ships. This complexity is partly responsible for the difficulty in relating requirements to vessel characteristics. To better understand the impact of requirements upon a ship it is useful to decompose the ship into a number of constitute parts. By examining these parts the interrelations within the ship design can be explored. However, considerable challenges arise when attempting to decompose complex systems into appropriate hierarchies[29]. A number of different decomposition approaches have been commonly applied to ships:

- Weight-Space Breakdown;
- Systems Engineering Hierarchy;
- Functional Group Breakdown.

and are now considered in turn.

These approaches bound the ship's constitute parts in different ways. Once the ship has been decomposed into a number of constitute parts the impact of requirements upon these parts can then be considered.

The weight-space breakdown, or classification, subdivides the ship's components into a number of groups related to the ship's principal components. This breakdown is an accounting system which uses the function of a space to determine which group the component is allocated to[30]. Table 2.8 shows the seven major weight groups employed within the UCL weight and space breakdown [UCL 2004] which is largely based upon UK MoD practise [MoD 2001]. Breakdowns of this type are often used within sizing models so that

[29] See the general discussion of this topic in Chapter 8 of [Simon 1981].

[30] Although historically the groups were based upon the different trades that existed within shipyards [MoD 2001].

significant amounts of past ship data may be available to the designer and to act as a completeness check. However, Andrews and Brown [1982] argue that the weight-space breakdown attributes excessive cost to the 'ship element' (cf. the 'payload' element) as items which directly support the payload are included as part of the ship's cost. This creates the impression that the 'payload element' is cheap, while the 'ship element' appears expensive.

Table 2.8: UCL Weight Groups

Group	Description
1	Hull
2	Personnel
3	Ship Systems
4	Main Propulsion
5	Electrical Power
6	Payload
7	Variables

Systems engineering is an approach devised in the 1950s for engineering projects which are either large, highly complex or both. In many ways systems engineering simply provides a framework for thinking about project managing engineering problems. The systems engineering framework is authoritatively summarised by the V-diagram which describes the overall systems engineering process, for one recent example see Figure 2.6. The left hand side of the V-diagram shows the successive stages of partitioning that transforms the users capability statement (produced after an initial 'requirements elucidation' process) via a requirements specification to designs of the overall system architecture, sub-systems and components. The right hand side shows the production, integration and testing processes which result in a viable solution, able to satisfy the original user requirements.

van Griethuysen [2000] provides a critique on systems engineering from a marine design perspective. He highlights the particular characteristics of marine vehicles which result in their design proving challenging for the designer attempting to apply systems engineering approaches, these include:

- The physical design and integration which exists within the marine vehicle;
- The design of systems dealing with the handling of data and information;
- The 'human factor'[31];
- The design of sub-systems (including the development and selection of equipment).

[31] With regards to the ship being a lived in environment.

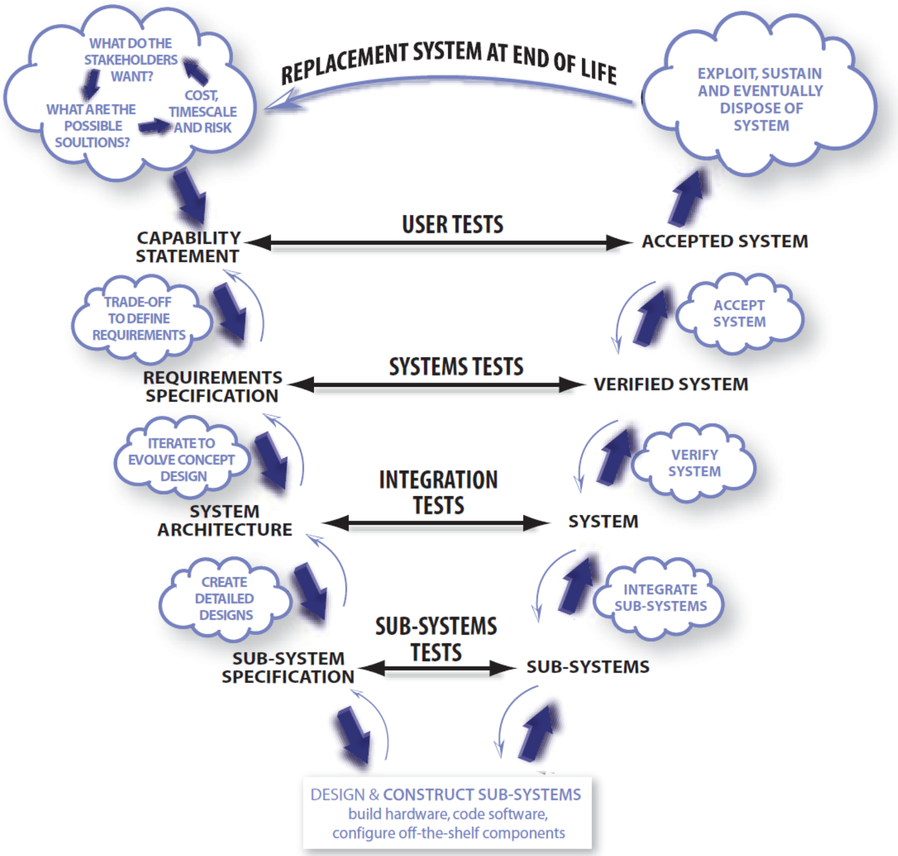


Figure 2.6: The V Diagram, from [Elliott and Deasley 2007]

van Griethuysen [2000] also describes the potential benefits of bringing engineering to the centre of the project management process; this is highlighted as a great merit of systems engineering, as is its ability to promote 'joined-up' engineering. However, current developments in systems engineering approaches have been led by engineers with a particular expertise in product areas such as software. This has led to an emphasis in some literature on system engineering methods which are incompatible with other classes of systems. van Griethuysen [2000] states that systems engineering is perhaps too generic a subject and that the system engineer needs some grounding in a specific technical domain. A view which Rydill [1969] supports.

The functional group breakdown, described first in [Andrews et al. 1996], separates the ship elements into one of several functional groups. The functional group breakdown was originally conceived in the case of a submarine [Andrews et al. 1996], with all elements of the vessel being allocated to either the Float, Move or Fight categories. But it was quickly realised that an Infrastructure group (containing items such as crew accommodation and supporting ship systems which would otherwise have been logically but impractically divided between the other functional groups) was necessary. The four groups, based upon [Andrews et al. 1996] that are now employed to functionally decompose a ship are:-

- Fight/Operations;[32]
- Move;
- Float;
- Infrastructure.

Table 2.9 gives an indication of the range of sub-functions that are encapsulated by the Float functional group. The table presents the sub-functions together with the principal objects affected by the sub-functions and the metric used to assess the sub-functions performance. Some metrics, such as the stability metric of vertical centre of gravity, describe a component of the performance of the whole ship. While the buoyancy of the Float group can be used to find a range of allowable values of vertical centre of gravity; its actual location is dependent upon the complete design (i.e. it is a whole body property). Similarly, whole body properties are also important to the metrics related to the seakeeping and cost.

Functional groups were originally introduced into the ship design process to help foster innovation [Andrews et al. 1996]. As a consequence, the use of functional groups allows the designer to examine how the overall requirements and characteristic of other groups affect any particular group. The introduction of functional groups has better exposed both the interrelations within the ship and the balance between the various functional groups [Andrews 2003b].

Due to the complexity of a ship design attempts made to decompose the ship into a number of sub-parts are non-trivial. The interrelation between different elements of the ship results in the creation of 'leaky-modules', where leakiness refers to the impact modules have upon each other [Erikstad 1996]. Differences between inputs and outputs of these leaky-modules indicate that the solution is unbalanced and therefore incomplete. Any imbalances must be resolved for the design to be complete.

2.4 The Performance and Characteristics of Alternative Hullforms

2.4.1 Hullform Style

It is possible to define a set of important aspects for the hullform, see Table 2.10. The examination of the hullform style draws on these aspects as part of the assessment of hullform characteristics.

[32]The Fight group is used within naval ships while Operations is used for commercial ships.

Table 2.9: Float Functional Group

Sub-function	Object	Metric
Buoyancy	Hull	Displacement Longitudinal Centre of Buoyancy
Stability	Hull	Vertical Centre of Gravity Metacentric Height Stability Standards[a]
Seakeeping	Hull	Sea-state vs. Response
	Stabilisers	Seakeeping Index
Resistance	Hull	Speed-Power Curve
	Appendages	Resistance Due to Waves
Volume	Hull	Internal Volume
	Superstructure	Internal Volume
Area	Hull	External Deck Area
	Superstructure	Internal Deck Area
Cost	All Contribute	Unit Procurement Cost Through Life Cost
Structure	Hull	Material
	Superstructure	Structural Life Assumed Still Water Loading

[a]Such as those described in Chapter 8 and 10 of [Biran 2003].

Table 2.10: Important Aspects of Different Hullforms, from [Lloyds 1988]

Aspect
Speed, Power and Endurance
Space, Layout and Weight
Structural Design
Intact and Damaged Stability
Seakeeping
Manoeuvrability
Military/Commercial Features
Construction Costs and Build Time
Through Life Costs

Determining which hullform is best matched to the requirements is difficult. Different requirements will drive the design process for different hullforms. It can be argued that the hullform is driven by one of three principal stylistic choices:-

- Sustension — The hullform's source of lift of the total weight (i.e. hydrostatic lift);
- Arrangement — The disposition of the hullform's internal layout (i.e. the general arrangement of fight or operations features, cabins and principal items of equipment);
- Topology — The arrangement of the hullform's constitute parts (i.e. the organisational configuration of the elements forming the boundary between the ship's internal systems and the external environment).

From these choices the hullform's style can be decomposed into three principal stylistic elements: Sustension Style; Arrangement Style; and Topological Style. The remainder of Section 2.4.1 discusses these issues and proposes some initial conclusions on hullform style.

Sustension Style

Sustension is a definition of the vessel's source of lift. Goubault and Allison [2003] present a discussion of the four sources of lift that are utilised by marine vessels, see Figure 2.7. Displacement craft with different hullform types are located at the same vertex of the pyramid (e.g. displacement monohull, catamaran, SWATH and trimaran).

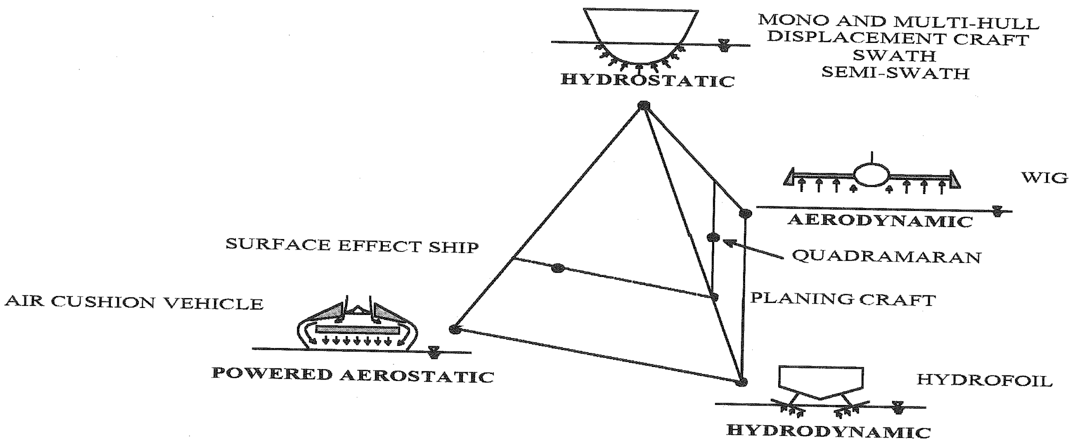


Figure 2.7: Sustension Pyramid, after [Goubault and Allison 2003]

Sustension is important, as selection of a different sustension style will radically alter the potential performance the vessel is able to achieve and the vessel characteristics required to meet this performance. This is most clearly displayed in the Von Karman-Gabrielli transport efficiency graph as shown in Figure 2.8. Shaded areas have been added to the diagram to highlighted the different performance by solutions with different sustension styles. The wide separation between the different sustension styles shows the separation of different hullform styles in terms of speed and the particular definition of transport efficiency adopted by Von Karman and Gabrielli (e.g. defined as the product of weight and speed divided by installed power).

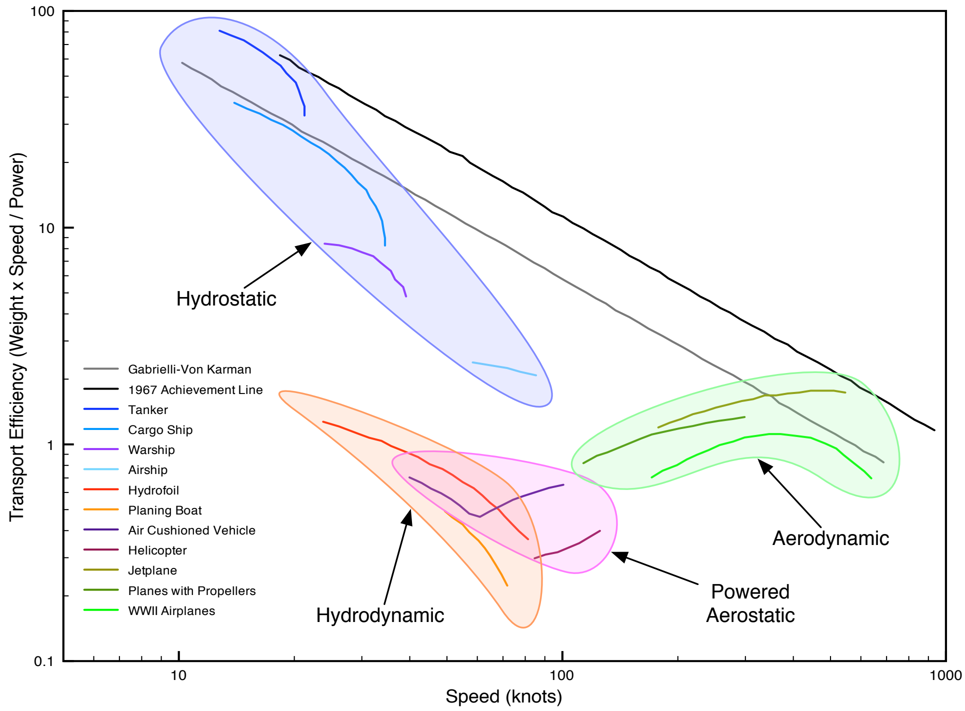


Figure 2.8: Von Karman-Gabrielli Transport Efficiency Graph, after [Insel 2000]

Arrangement Style

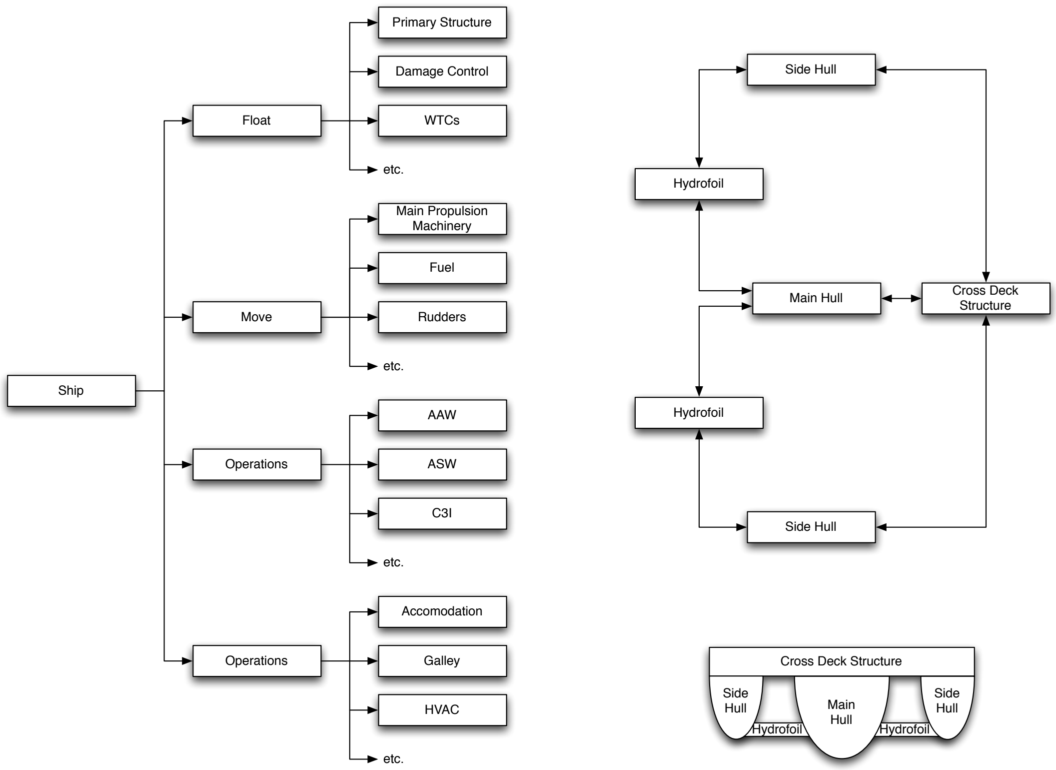
Arrangement is a critical factor of any ship design as it has a substantial impact during the ship design process. The importance of arrangement to the design is stated by Andrews [1981] who questions the basic assumption that “all space is equally important” (as is the case with weight), an assumption that is inherent in many sizing methods utilised at the early stage of the design process. A comprehensive discussion on the importance of arrangement, or architecture, in ship is presented in [Andrews 2003a].

Topological Style

As discussed earlier, in this context topology is being used to describe the organisational configuration of the elements which form the boundary between the ships internal systems and the external environment. Considering the hullform, this provides the elements which determine the ship’s hydrostatic and hydrodynamic lift. However a number of topologically different solutions are possible which are equivalent in terms of sustension, such as: monohull, catamaran and trimaran. Similarly, there are conceivably an enormous possible number of different solutions with identical external forms, and hence topologies, but different internal arrangements.

By describing a hullforms topological style as the configuration of a system's constituent parts it provides a bridge between the vessel's external interface and its constituent systems. Furthermore, this definition of the vessel's topological style is distinct from the arrangement style as it describes gross factors which are of particular influence to the arrangement.

While some gross performance characteristics are driven by sustension style (as illustrated in Figure 2.8), different topological styles can lead to marked differences in vessel performance. Examples include: the number and location of hulls; locations where dynamic lifting surfaces are attached to the structure; and, propulsor positions. However, the viability of the solution as a whole is met by ensuring the vessel's internal systems satisfy both the external demands (driven by the sustension style) and internal demands (driven by both the arrangement style and the styles adopted by the ship's systems). Figure 2.9 is an example of a ship decomposed both by functional design building blocks and through a topological structure, Figures 2.9a and 2.9b respectively.



(a) Functional Building Blocks

(b) Topology for Partially Hydrodynamically Supported Trimaran

Figure 2.9: Functional Design Building Blocks and Topology

The choice of topology will affect some functional design building blocks; for example, as the overall vessel shape is altered structural weight will change. Alternatively, the choice of a particular configuration of hullform elements may impact upon the systems required within the ship[33]. Some connection between the topological and functional representations of the ship must be introduced. Figure 2.10 shows the two representations linked through the introduction of some example performance capabilities[34].

The topological style adopted by the ship heavily influences the performance the ship is able to achieve. A description of the ship's style gives a broad definition of the likely level of performance. However, the actual performance may differ significantly from such a prediction.

Conclusions on Hullform Style

Collating together the points discussed in the previous section it is possible to identify the aspects from Table 2.10 which are driven by Sustension, Arrangement and Topology as shown in Table 2.11. The different sustension, arrangement and topology styles impact on different aspects of the vessel's overall performance by varying degrees. Given the impact of stylistic choices the current methods adopted for undertaking this decision making step are of interest and are discussed in the following subsection.

2.4.2 The Advantages of an Alternative Hullform Style

One example of the advantages of different hullform styles is presented by Betts [1988]. He provides a review of comparative studies of Monohull and SWATH hullforms at that time, which described the difficulties of developing a fair measure of equivalence between the different hullforms. For example, while a SWATH may possess good seakeeping characteristics, a monohull can be modified to attain comparable motions. In particular, Betts highlights a study by Kennell et al. [1985] comparing Monohull and SWATH hullforms for towed array sonar operations. In that study three comparable ships were presented: a baseline payload-driven monohull; an equivalent payload SWATH; and, an equivalent seakeeping monohull. Profiles of the three ships and one of the performance metrics assessed by Kennell et al. are reproduced in Figure 2.11.

In order to meet the same payload carrying capacity as the baseline payload-driven monohull, the equivalent payload SWATH had to be 30% greater in displacement. This

[33] Taking for example a trimaran fitted with dynamically controlled roll damping foils. Moving the foil from the sidehull to main hull will result in a significant physical rearrangement of functional design building blocks to provide the required actuation forces.

[34] Figure 5.4 in [Andrews 2003a] highlights a subset of design issues that fall under the topic of design integration. Andrews defines these as project issues (the '-ilities') that are distinct from the ship systems (represented through the four functional groups). Together the project issues and ship systems form the total ship description. An alternative breakdown to that shown in Figure 2.10 is needed to allow the representation of these issues.

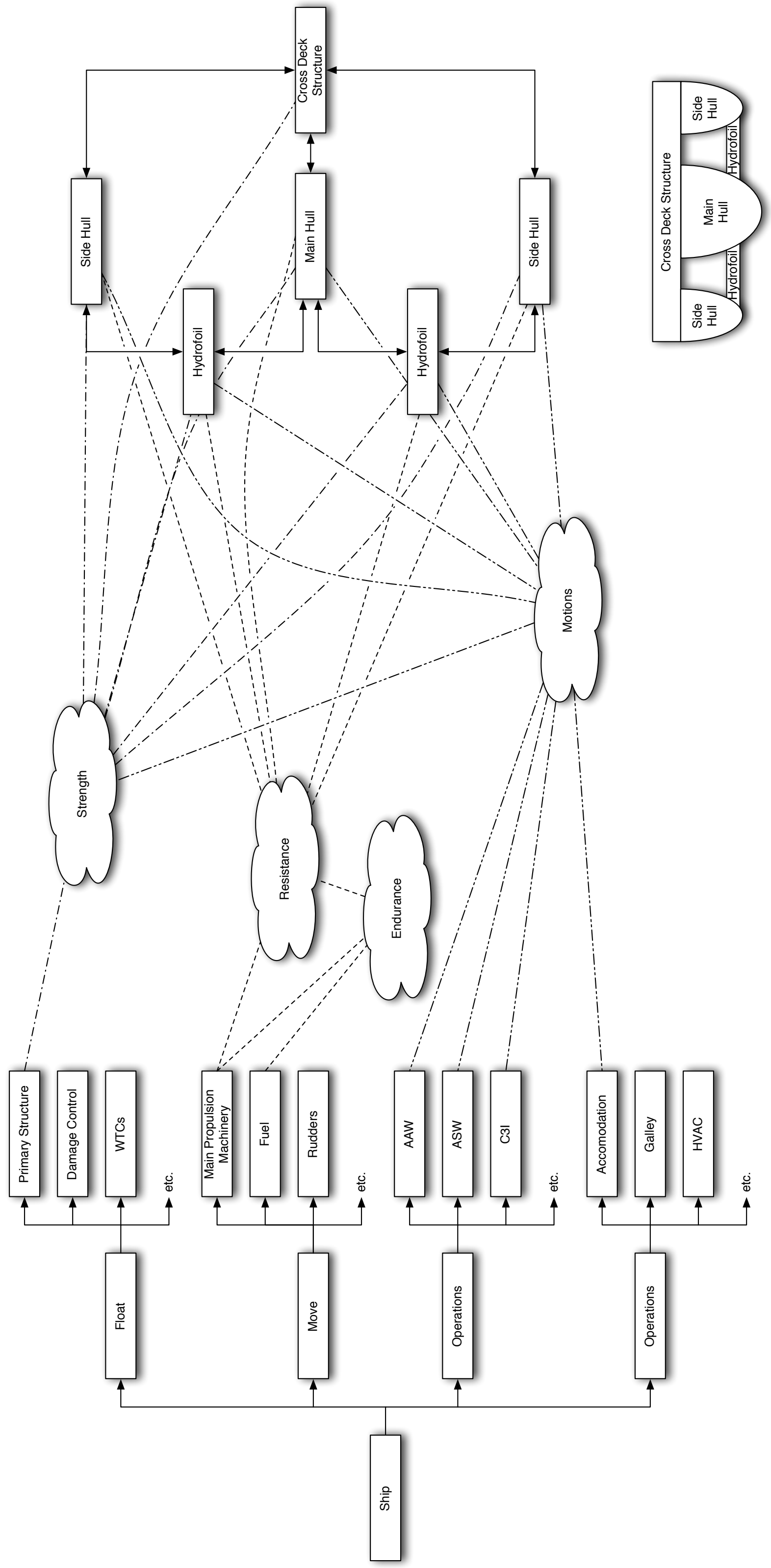


Figure 2.10: Function Design Building Blocks and Topology Connections

Table 2.11: Relation of Sustension, Arrangement and Topology to the Important Aspects of Different Hullforms

Aspect	Sustension[a]	Arrangement[a]	Topology[a]
Speed, Power and Endurance	•••	•	••
Space, Layout and Weight		•••	•
Structural Design	•	••	•••
Intact and Damaged Stability	•	•••	•••
Seakeeping	•••	•	••
Manoeuvrability	•••	•	••
Military/Commercial Features[b]		•••	•
Construction Costs and Build Time	•	••	•••
Through Life Costs	•	••	••

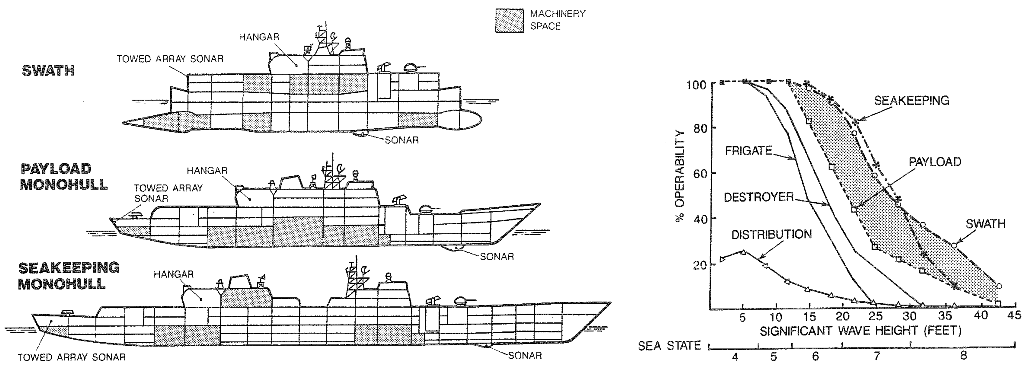
[a]Where ••• indicates a highly significant impact, •• a significant impact and • a limited impact.
[b]For example, in the case of a naval vessel these features include weapons systems, sensor systems and the vessel's signatures.

growth was mainly due to an increase in structural weight of the SWATH. However, the SWATH's reduced waterplane area led to a decrease in wave excitation forces resulting in the SWATH exhibiting reduced motions in a seaway. For a monohull to have equivalent seakeeping performance to the level predicted for the SWATH required a growth in the monohull's displacement of 70% (this 'seakeeping monohull' is shown in Figure 2.11). The increase in structural weight caused by the growth in size was some 106% over the 'payload monohull'. In essence, the SWATH is more sensitive to payload growth while the monohull is more sensitive to seakeeping requirements. This sensitivity of particular hullforms to certain requirements presents a significant problem in the early stage of the design process when the designer and customer wish to rapidly explore emerging requirements.

2.4.3 The Comparison and Selection of Hullforms

The selection of hullform style is of considerable interest and has been explored by many authors[35]. [Andrews 2001], [Eames 1985] and [MoD 2005b][36] provide a qualitative assessment of different hullforms. The change in vessel characteristics which can be achieved through the selection of an alternative hullform is discussed in [Andrews 2001] where it is argued that the benefits which can be realised through the selection of the 'correct' hull-

[35]In chronological order Andrews 1981; Eames 1985; NATO 1987; Lavis et al. 1990; NATO 1997; Sadden and Nisbet 1998; Broadbent and Kennell 2001; Goubault and Allison 2003; McDonald et al. 2004; NATO 2004.
[36]In particular Table 3-4 in [MoD 2005b].



(a) Ship Inboard Profiles (b) Relative Ship Operability

Figure 2.11: Comparison of Swath and Monohull Designs, from [Kennell et al. 1985]

form for a given task will be substantial[37]. This can be seen in Table 2.12 from [Andrews 2001] which provides a qualitative assessment of the strengths and drawbacks of a range of hullforms. Given the difficulty in assigning quantitative measures of merit, naval architects typically use such qualitative assessments based upon their own personal experience in the selection of hullforms.

Table 2.12: Qualitative Assessment of Different Hullforms, from [Andrews 2001]

Ship Types / Aspects (Table (1))	Monohull	Catamaran	ACV	SES	Hydro-foil	SWATH	HYSWAS	WIG	Trimaran
Speed, Power and Endurance	Good	Good[1]	V Good[2]	Good	V Good[2]	Good	Good	V Good	Good
Space and layout	Good	Good	Ave	Good	Poor	V Good	Poor	Poor	V Good
Structural design and weight	V Good	Ave	Poor	Poor	V Poor	Ave	Poor	V Poor	Good
Stability	Good	Good	Good	Good	Good[3]	Good	Good	Poor	V Good
Manoeuvrability	Good	Ave	Poor	Good	Good	Ave	Good	Poor	Good
Noise, Radar and Magnetic Signature	Good	Ave	Good	Good	Good	V Good	Good	Good	V Good
Weapon placement and effectiveness	Good	Ave	Ave	Ave	Poor	Good	Ave	Poor	V Good
Construction costs and build time	V Good	High	V High	High	V High	Good	High	V High	Good
Through life costs	Good	Ave	V High	High	V High	Ave	High	V High	V Good

Notes:
1. But bad in deep ocean seaway.
2. Very fast but limited to hull borne (slow) in seaway and endurance poor (fuel weight).
3. Very good hull borne but foil borne degraded by wave effects in deep ocean.

[37] The paper focuses upon the need for adaptability within naval combatants and recommends the trimaran as an adaptable hullform.

Other published work has attempted to perform quantitative analysis of different hullforms to find those best suited to a role. This has taken the form of comparative studies for more specific requirements by exploring the effect of changing the hullform style on the solution's characteristics [Sadden and Nisbet 1998; Lavis et al. 1990; Broadbent and Kennell 2001; McDonald et al. 2004]. The hullforms explored in these references is summarised in Table 2.13.

Table 2.13: Quantitative Hullform Comparisons

Reference	Monohull	Catamaran	Trimaran	SWATH	SES	ACV	Hydrofoil
[Sadden and Nisbet 1998]	•	•	•	•			
[Broadbent and Kennell 2001]	•	•	•		•		
[McDonald et al. 2004]	•	•	•		•		
[Lavis et al. 1990]				•	•	•	•
[NATO 1987]	•			•	•		•
[NATO 1997]	•			•	•		
[NATO 2004]	•	•	•	•	•	•	•

Finally, a number of NATO reports contain analyses of different hullforms and an assessment of the potential for novel craft to meet NATO's perceived future naval requirements [Eames 1985; NATO 1987; Lavis et al. 1990; NATO 1997, 2004]. The perceived benefits of a range of hullforms were discussed in these studies. [Lavis et al. 1990] summarised the work performed by the NATO Special Working Group Six (SWG/6), whose remit was to explore the potential of advanced marine vehicles. One particularly important comment from [Lavis et al. 1990] highlights the difficulty of ensuring comparative studies are objective:

> "It is this second issue (objectivity) that led to the development of a joint parametric study for SWG/6 between the United States (US) and West Germany (GE). One problem that occurs when comparisons are made is that many people become involved because of the magnitude of the project and each has his own analytic methods, preferences and biases. As a result different standards, margins and practises are often employed so that each of the hullforms are not always designed to the same standard, resulting in the proverbial 'apples and oranges' comparisons. Even the use of computerised design-synthesis models does not always eliminate this problem since the programs are generally written by different people, or organisations, and for different purposes."

More recent examples of NATO's continued interest is presented in [NATO 1997] and [NATO 2004]. [NATO 1997] summarises work by NATO group SWG/6 which was responsible at that time for investigating the potential of unconventional craft. The report contains four annexes related to the design of unconventional craft:

- Craft types and design information on alternative hull types;
- Parametric design data for three alternative hull types;
- A glossary of analysis methods and tools able to support the assessment and selection of alternative hull types;
- Examples of the application of the analysis methods to cost and operational effectiveness analysis[38] studies.

The parametric design data found in this publication could still be used during the appraisal of different hullforms. It comprises a series of plots demonstrating the performance of different hullforms and machinery options. However, there is a risk of such parametric data becoming obsolete[39]. An approach that enables the addition of new information would be a substantial development.

2.5 Case Study: Exploring Different Hullforms for the Littoral Combat Ship

The candidate in [McDonald et al. 2004] presented an example of a hullform comparison study meeting the US Navy Littoral Combat Ship (LCS) requirements; the full paper is included as Appendix A. The study takes the LCS requirement [US Navy 2003] as a baseline and then demonstrates how this might be satisfied using a range of hullforms: monohull, trimaran, surface effect ship (SES) and catamaran. The advantages and disadvantages of these four hullforms against the published LCS requirements were explored by developing a numerical sizing model. The sizing model automatically explored large variations in the ship's payload, examining 7200 different payload combinations, from which the cost and benefit (in terms of payload capability for a fixed set of ship performance capabilities were found). These results were used to inform a cost–benefit analysis that highlighted the options that defined a pareto-frontier[40]. From this analysis one option for each of

[38] Abbreviated to COEA. This definition follows that used within [NATO 1997]; the report defines the UK equivalent at that time as Cost and Operational Effectiveness and Investment Appraisal (COEIA).

[39] For example, the recent introduction of a new generation of high powered and efficient gas turbines, such as the Rolls Royce MT-30 [Rolls-Royce plc 2009], is not reflected in the results predicted by the parametric design data within [NATO 1997].

[40] A Pareto frontier defines the subset of a given a set of choices which are Pareto efficient given a specific way of valuing each alternative. By assessing the pareto frontier a designer can rapidly examine a solution space. Recent research at UCL has explored the utility of this information in elucidating

the four hullform was selected for further development. The selected options had a total cost matching the LCS target cost of $220 million [US Navy 2003]. These options were developed into detailed point designs to validate the numerical sizing model used to develop the designs, these designs are shown in Figure 2.12. The detailed point designs exposed a number of key design drivers for each hullform. Furthermore, the payload carrying capability of the four hullforms (all able to meet the requirements) was found to vary. In terms of payload carrying capability the study ranked the hullforms in the following order (from most to least cost-effective): Trimaran; Monohull; SES; and Catamaran. This assessment demonstrated that for the four hullforms considered the trimaran and monohull were the most cost-effective solutions to the LCS requirements. Furthermore, the choice between different hullform types was shown to have considerable impacts on overall vessel capability and highlighted the necessity to examine different hullforms in the early stage of the concept design process.

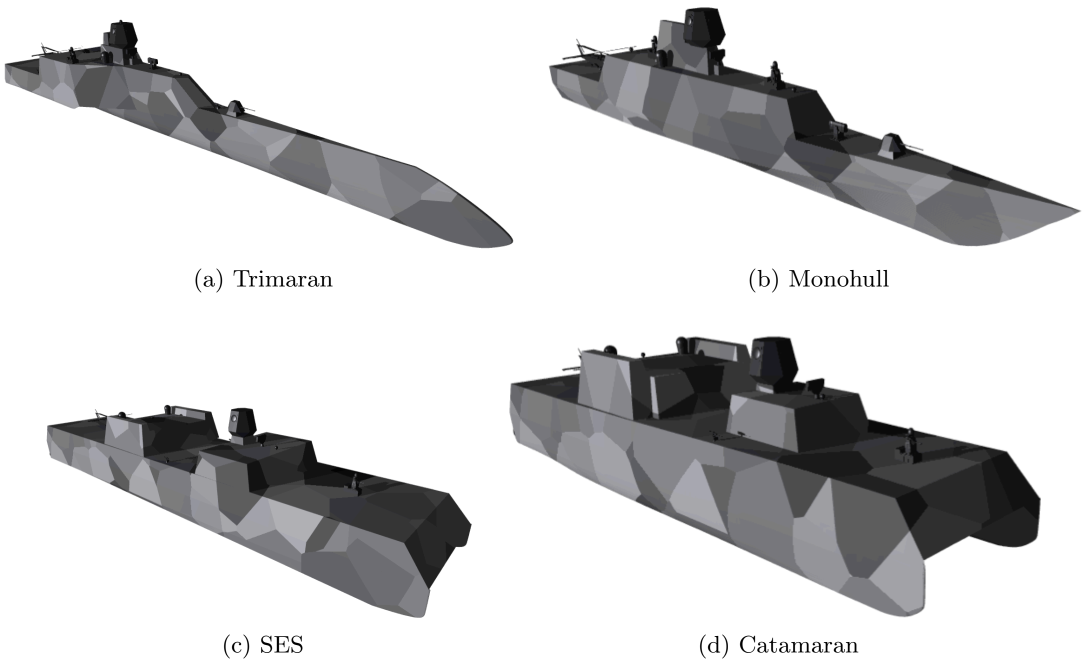


Figure 2.12: LCS Point Designs, from [McDonald et al. 2004]

One outcome of this case study was the identification of significant issues in applying performance prediction tools to a range of hullforms. Powering predictions for the LCS were likely to be challenging, considering the required high speed. The study has highlighted the lack of accurate ship resistance prediction methods valid at the high speeds required by the LCS (40+ knots). Potential speed/sea-state limitations for the various configurations

requirements during ship concept design [Vasudevan 2008]. In this case the set solutions developed for the different of payload options were restricted to the set of choices that are Pareto-efficient in terms of their cost-benefit.

were not able to be determined due to a lack of tools. Accurate prediction of the structural weight in the concept phase was not possible due to the large variation in the loading conditions of the competing hullforms. The study identified a lack of data available in early stage design, to predict the structural weight of multihull craft.

The current generation of performance prediction tools for resistance, seakeeping and structural weight estimation all require highly detailed ship definitions. There is a requirement for a set of performance analysis tools more suited to initial design when less is known about the ship. Two viable approaches seem possible to developing tools able to bridge the gap between existing complex analysis tools and a low design definition: either, simplified analysis tool that require limited inputs (and have limited capabilities) [Schofield 2007]; or, developing tools able to automatically “fill in” missing design detail using appropriate default values, patterns or styles. Ideally, these tools should give results for a large range of possible ships types and sizes, together with a confidence level for predictions, particularly in the areas of structures, seakeeping and powering that are significant size and cost drivers.

2.6 Conclusions on the Hullform Selection Problem

This chapter has outlined the importance of the initial step of the ship design process—the Concept Phase. This phase sees a number of key choices being made at the start of a complex decision making environment. The complexity of ships and the complexity of design are both important contributory factors. Given this complex decision making environment, the key choices made by the designer are further complicated by numerous constraints acting on a given design, the design process used and the design environment in which it takes place. The combination of complexity and constraints may preclude a full examination of alternatives—such as different hullforms style. This then prematurely excludes alternative solutions that may offer substantial benefits. There is a need for a tool to enable a designer to explore alternative hullforms in the early stages of the ship design process to greatly facilitate effective requirement elucidation.

3 Current Ship Concept Design Approaches and Implementations

Chapter 2 identified the importance of a design tool in allowing the designer to explore alternatives as fundamental to the requirement elucidation objective of the concept phase of the ship design process. This chapter discusses current ship design approaches and their implementation to discover their suitability for this task. It begins with a discussion of the types of ship design. Next, Section 3.2 considered seven types of ship design approaches able to support some or all of these types of ship design, these are:

- Traditional Ship Design Approaches;
- Concept Exploration Based Approaches;
- Optimisation Based Approaches;
- Decision Making Based Approaches;
- Artificial Intelligence Based Approaches;
- Configuration Based Approaches;
- Set Based Approaches.

The role the designer adopts in the decision making process for these seven approaches to ship concept design is then discussed. Following this overview of the different approaches to ship design Section 3.3 focuses on two approaches, the traditional ship design approach and Andrews' configuration based approach, using these as illustrative examples to examine the important synthesis step that occurs within the design process. This examination highlights the importance of selecting style at the outset of the design process. Section 3.4 then presents two sets of ship concept design tool requirements developed by other authors. The chapter concludes by discussing the ability of existing design approaches to rapidly explore different alternative hullform styles; while the designer is working to elucidate requirements in the concept phase.

3.1 Ship Design Types

Andrews defines seven types of ship design, in terms of novelty, ranging from simple subsequent further batch designs right through to solutions employing radical technology [Andrews 1998]. These types are shown in Table 3.1. [Andrews 1998] has also proposed that the process of ship design can be separated into three categories: designing to the current state of the art; developing the current state of the art; and redefining the current state of the art. These categories reflect the degrees of uniqueness described by [Gale 2003].

Table 3.1: Types of Ship Design, from [Andrews 1998]

Type	Example
Subsequent Batch	Batch 2 Type 22 Frigate
Type Ship	Most naval auxiliary vessels
Evolutionary	VT Shipbuilding's Family of Warships [Usher and Dorey 1982]
Simple Synthesis	UCL student designs [UCL 2002]
Broader Synthesis	UCL integrated design approach [Andrews 1986][a]
Radical Configuration	SWATH, Trimaran
Radical Technology	Hydrofoil, SES

[a] And further developed in [Dicks 2000] and [Pawling 2007].

Of the seven types of ship design, Subsequent Batch, Type Ship and Evolutionary design types allow the designer to develop ships based upon the current state of the art. Subsequent Batch and Type Ship[1] provide the designer with a capability for undertaking the simple reproduction of previous ships with only minor modifications. Evolutionary design is able to slightly develop the current state of the art.[2]

Simple Synthesis, Broader Synthesis and Radical Configuration types of ship design are appropriate when exploring novel design concepts. These three types of ship design are more able to address a challenging requirement. They possess the potential to design a 'new' ship as they employ a synthesis process able to respond to challenging requirements by exploring different alternatives. However, the simple synthesis process is heavily dependent upon the information that forms the current state of the art. It is therefore lower risk but less suitable for designing to meet more novel needs or options.[3]

[1] Considering the example of a container ship different options for type design may be considered including extending the parallel midbody, or improving the machinery fit within the aft of the ship [Meek 1970].

[2] Evolutionary design, as performed by shipyards, leverages the large amount of knowledge obtained from developing and building a given ship. This knowledge can be used to develop an incremental improvement to the design.

[3] The design procedure as undertaken during Ship Design Exercise at UCL can be considered to be an example of simple synthesis. The synthesis process from the design exercises uses a definition of payload

The final category of Radical Technology is distinctly different from the other six types of ship design. It incorporates technology from outside the marine industry, and requires resource intensive approaches such as prototypes and production methods commonly employed within the aerospace industry (i.e. design and build new production facilities). These types of approaches are rarely adopted in the marine sector where large prototypes are uncommon and such development costs unattractive. Also, the incorporation of any new radical technology will substantially widen the range of designs which could be contemplated, however greater risks require considerable development investment.

Three of the ship design types are typically associated with design problems that feature the exploration of different hullforms:

- Broader Synthesis;
- Radical Configuration;
- Radical Technology.

A genuinely comprehensive ship design method should possess the flexibility to support these types of ship concept design. However, many commercial organisations favour the adoption of more conservative design methods as they are usually risk adverse.

3.1.1 Ship Design Types Adopted by Industry

In considering ship design problems it is useful to consider the approaches taken by UK commercial organisations to ship design as they can provide a different perspective from that commonly presented in academia. It is clearly important to understand industry's outlook to ensure any design process developed is suited to the needs and constraints of the 'real world'.

Larger commercial organisation such as shipyards tend towards adopting traditional ship design methods, such as: subsequent batch, type ship and evolutionary designs, as defined in Table 3.1. This is most apparent in the different design organisation's families of ship: VT's OPV [Usher and Dorey 1982]; BAE System's Fxxx series. This approach is driven by a desire to minimise risk by leveraging past design information and solutions. Shipyards very rarely develop wholly new ships. While effective in minimising risk, this approach is far from ideal from a concept design perspective where the exploration of novel solutions is of principal interest.

to estimate a complete space and weight for the whole ship. From these whole ship estimates the weight and volume of the ship's components are calculated and summated to obtain a revised whole ship weight and volume. This calculation step is iterated until the ship is balanced. Weight breakdowns for previous ships form the basis algorithms of this approach therefore the range of ships which can be considered by these methods is limited [UCL 2002]. However, if the designer wishes to consider a design with a radical configuration then a more complex geometry model must be employed to inform the values of weight and space. Consequently design uncertainty increases rapidly as the designer moves away from the limited knowledge base upon which existing weight and space relationships are based [Dicks 2000].

To promote design flexibility several shipbuilders have adopted a design approach that Park and Storch [2002] described as modular parametric design that encourages reuse during design. Ishikawajima-Harima Heavy Industries of Japan employ a module reuse philosophy with only minor modification being made to individual modules [Baade et al. 1998]. Thyssen Nordssewerke of Germany utilised generic machinery unit sets, allowing a separation of the design of machinery unit and hull structures [Jaquith et al. 1988]. This approach is also echoed in mission modularity systems, such as Meko and StanFlex which are described in [NATO 2004]. These modular and adaptable approaches are justified in the belief that they allow the reuse of significant elements of previous solutions without significantly constraining the arrangement of the new solution. However, it also acts to form a clear systems interface thereby separating combat system uncertainties from the design of the ship's outfit.

The commercial pressures that arise in the shipbuilding industry create further pressures upon the design process leading to the adoption of a conservative approach to ship design. The shipbuilding industry tends towards adopting the following types of ship design:

- Subsequent Batch;
- Type Ship;
- Evolutionary.

More novel UK commercial ship design work not conforming to the subsequent batch, type ship or evolutionary types of ship design has recently been undertaken by a number of organisations. BMT Defence Services Limited have developed ship and submarine designs such as the Aegir, Vidar and Venator [Aitken and Jones 2007; Binns 2008; Kimber and Giles 2008; Kimber et al. 2008]. Other ship design work on the UK MoD's Military Afloat Reach and Sustainability (MARS) project exploring possible replacements for the Royal Fleet Auxiliary fleet tankers, which the candidate was involved with, has explored the application of broader synthesis types of ship design [Cooper et al. 2007].

Some parts of the commercial ship design community are moving towards exploring arrangement and layout at an earlier stage of the concept design process [Andrews et al. 2005; Andrews and Pawling 2007]. By evaluating materially different design options there is far greater potential to expose radical solutions which could then better satisfy a set of requirements or even open up the requirement space. Limiting the solution search space to previous solutions, or small modifications of these, risks impeding the range of solutions explored within the early ship design process.

One interesting example from the commercial ship design field is the system based design approach proposed by Levander [1992, 2003]. This approach (implemented via a tool termed 'SeaKey') adopts a system based decomposition to divide the vessel into 'payload' and 'ship' functions (and then further into other sub-functions). Characteristics (e.g.

weight, volume) are estimated for the different (sub-)functions based upon an extensive database of design knowledge collected at shipyards. This then allows the calculation of main ship design parameters such as principal particulars, deck area allocation, volume allocation, weight breakdown and construction cost. As the design is developed in more detail balance is assessed across key naval architecture areas (e.g. weight balance). Levander's system based design approach allows the effective utilisation of large quantities of prior knowledge on past solutions, but importantly by adopting a functional breakdown it encourages other, more radical, options to be considered for different functions or sub-functions.

Design consultancy organisations tend towards adopting the following types of ship design:

- Simple Synthesis;
- Broader Synthesis;
- Radical Configuration.

In contrast to the subsequent batch, type ship and evolutionary types of design commonly adopted in the shipbuilding industry, the types of design adopted by design consultancy organisations may consider alternative hullforms. However, in cases where an alternative hullform may offer advantages commercial organisations (or their customers[4]) have experienced problems in rapidly determining the most appropriate hullform for a given set of requirements. As described in Section 1.1.1 the US Navy's Littoral Combat Ship programme explored different hullforms via a multiphase competitive competition that concluded with the evaluation of two full size prototype ships with differing hullforms. The program spent over $500m attempting to select the most appropriate hullform for a ship with a radical concept of operations. If a design approach or method able to explore multiple hullform option had been available to the US Navy some of this expenditure might have been avoided. Having such an exploratory facility could remove a significant hurdle to the consideration of alternative hullforms, allowing possible superior alternatives to be more readily explored.

3.2 Ship Design Approaches

This section examines current approaches to ship concept design with the intention of revealing if they could assist the concept designer in exploring hullform options in the early stages of the ship design process.

[4]If alternative hullform offer better performance then the impetus to adopt these solutions may originate with the customer. However, the customer will still require assurance that these design options provide real benefit necessitating a full exploration during the requirement elucidation phase.

3.2.1 Traditional Ship Design Approaches

Traditional ship design approaches are typified by a designer led exploration of a single solution and possible variants. Such approaches are discussed in [Watson and Gilfillan 1976; Brown 1983; Watson 1998; UCL 2002; Price 2002a; Brown and Moore 2004].

Traditional design approaches have developed over a long period, parallelling the development of both naval architecture and engineering design. A review of the genesis of the numerical and scientific approach to ship design is given in [Ferreiro 2004]. Brown provides a description of the evolution of the ship design process within the UK Ministry of Defence [Brown 1983]. In particular, he describes the simple mathematical models of a ship design which enabled trade-off studies to be conducted at an early stage of the design process[5]. Brown indicates that a considerable amount of time was required to perform the calculations by hand, even at the earliest stages of ship design process. The progression from hand calculations to design with computer assistance adopted by the Royal Corps of Naval Constructors is described within [Brown and Moore 2004]. Most recent design approaches that used numerical synthesis have adopted digital computers as a calculation tool[6]. For the procedure undertaken by students at UCL, numerical synthesis is provided through a set of weight and space algorithms applicable to particular ship types [UCL 2002][7]. Similar models have been developed elsewhere [Price 2002a].

There are substantial benefits in the flexibility of the traditional ship design approach. In particular, a wide variety of solutions can be developed to explore the impact of varying characteristics, such as speed and endurance. However, apart from the case of simple synthesis, traditional ship design approaches have been limited by available data, as described previously in Section 3.1. Therefore, considerable judgement is required if the features of the design differ widely from previous experience and their ability to explore radical options is therefore constrained by the judgement of the designer. The traditional ship design approach is a designer driven process where the designer performs both the calculation and decision making role, which means the underlying methods are inherently flexible. Therefore, if a designer is sufficiently skilled then these methods should be able to explore significant changes to the design, including investigating the consequences of particular design decisions[8].

The designer may also be able to gain an understanding of the impact of requirements where there is limited design data. Limited design data occurs with the radical configuration and radical technology types of ship design from Table 3.1 and also with the

[5]Models such as these are known as 'weight equations' and related the estimated weights of the ship to the armament, complement, power and endurance.

[6]These approaches enable very rapid design iterations to be undertaken, allowing different variants within a specific range of applicability to be quickly assessed.

[7]With any of the weight equation there is often substantial difficulty in obtaining accurate and up to date weight and space data for the ship types being designed.

[8]If sufficient data is available to the designer.

introduction of new major equipment being concurrently developed with the ship design (i.e. combat and propulsion systems). These ship types often offer the most potential for radical improvement but suffer from insufficient technical knowledge to accurately determine performance. While manual design methods can deal with gaps in knowledge more easily than automated methods, their performance in this task is highly dependent upon the skill, knowledge and prejudices of the designer.

3.2.2 Concept Exploration Based Approaches

Concept Exploration Models (CEM) utilise the rapid symbol processing ability of computers to facilitate an exploration of a design space. CEM's work by developing a range of solutions, then allowing the designer to explore the solutions characteristics and properties. CEM's take as inputs principal ship and operational requirements. These are then used to determine ship geometry, stability, performance and other vessel characteristics. The developed designs are then assessed by the designer to find a feasible design which satisfies the requirements. The validity of the results for any CEM will be determined by the accuracy and limits of the mechanism used to develop and assess the designs. To date current CEM's have been designed around particular types of ships.

A large number of authors have explored applying CEM to the design of ships [Eames and Drummond 1977; Nethercote and Schmitke 1982; Smith et al. 1987; Smith 1992; Smith and Mistree 1994a; Erikstad 1994, 1996; Price 2002b; Simpson et al. 1996; Molland and Karayannis 1997; Whitfield et al. 1999; Lavis and Forstell 2000]. A comprehensive description of the workings of a simple CEM for designing 1000-6000 tonne monohull warships is given in [Eames and Drummond 1977]. Advanced hullforms have been explored through CEM. For example, [Nethercote and Schmitke 1982] demonstrated the application of a CEM to SWATH ships. [Smith et al. 1987; Smith 1992; Smith and Mistree 1994a] detail the application of a CEM as part of a larger design system. Erikstad [1996] presents an decision support model for preliminary ship design that features a CEM—'ShipX'—that demonstrated a framework able to 'generate', 'analyse', 'evaluate' and 'decide' upon a range of options. Recent developments in CEM have seen a move to whole-ship design synthesis models which emphasises the use of physics-based algorithms [Balasubramanian and Lavis 2001].

One interesting example of a concept exploration method is the 'portfolio of ship designs' approach presented in [Schiller et al. 2001]. This uses a number of databases to store the following types of design information: parent hullforms; vendor equipment (e.g. prime movers, reduction gearing and generator sets); light ship weights; and ship costs. Using design information retrieved from the databases options are synthesised using a conventional iterative sizing process and then checked against stability, speed, range and cargo carrying capability to develop an acceptable solution. However, this approach still requires a time-consuming synthesis model to be run while the designer is using the tool.

Smith and Mistree [1994a] detail the application of a CEM as a key initial part of a larger design system. Their paper summarises an example of a five day long design study (derived from [Smith 1992]) that employed a software based design system called DSIDES. This system was intended to assist the designer in learning about the design space. One early element of DSIDES, called EXPLORE, allowed the designer to apply a CEM to explore regions of the design space. EXPLORE employed a single design synthesis model which is used by the CEM to investigate options between upper and lower bounds. DSIDES next employs the decision support problem technique [Mistree et al. 1990] together with trend analysis, optimisation and robustness analysis to develop final recommendations. In the discussion of their paper, Smith and Mistree also make reference to a 'rapid concept exploration method' (under development at the time) intended to assist in identifying important variables during the start of the design process [Smith and Mistree 1994b].

CEM provide a powerful mechanism for enabling the designer to develop an understanding of the design space. However, they do not directly provide guidance to the designer on where better solutions may lie. The Response Surface Methodology (RSM) is one extension of the CEM able to produce a model suitable for design guidance [Price 2002b]. The RSM is a statistical process which can be used to study the empirical relationship between inputs and outputs (termed factors and responses respectively). A design space is specified in terms of a range for each factor. A Design of Experiments process is used to determine the minimum amount of actual designs from within the space to be assessed [NIST 2009]. This then allows an accurate regression analysis of the design space to create a response surface which defines a relationship between the factors and responses of the design space. Using this response surface the RSM deploys standard optimisation techniques (e.g. genetic algorithms) to find a 'suitable' design based upon a set of user defined objectives. This method can be seen to parallel the process of the CEM, but with the decisions on the design search space driven by previously prescribed optimisation technique and the mathematical relationship that defines the response surface, as opposed to the designer and a synthesis tool. These decisions are encapsulated within the criteria specified by the designer within the optimisation technique. Applications of the RSM to ship design can be found in [Whitfield et al. 1999] and [Price 2002b].

For both CEM and RSM it is potentially difficult to define the limits of the search space; a trade-off exists between broadness, accuracy and computational expense [Erikstad 1996]. Various strategies can be employed to ensure a wide solution space is explored in a computationally efficient manner. However, the designer must ultimately determine the scale and discretisation of the examination of the solution space. Within the field of aircraft design methods for effectively presenting design information on a larger number of alternatives, with similar configurations have been proposed [Goel et al. 1999]. Recent work, with which the candidate has been involved, has explored the use of commercial design approaches, optimisations and visualisation tools to explore the design space for naval auxiliary vessels [Cooper et al. 2007; Horner 2009].

CEM have demonstrated the ability to assess different styles concurrently. [Molland and Karayannis 1997] presented a CEM, underpinned by a database centric framework for storage of designs, which provides the designer with the ability to asses several advanced marine vehicles concurrently. This work only employed a CEM to select between two hullforms for a single, well defined commercial ferry role. However, the area centric synthesis method that Molland and Karayannis' design approach adopts limits the CEM to the evaluation of area driven designs, this constrains its suitability for exploring a large range of ship with differing roles. This inability to design an arbitrary ship type[9] is a fundamental issue with many existing CEM.

3.2.3 Optimisation Based Approaches

Optimisation based approaches share several characteristics with CEM. Section 3.2.2 has suggested that CEM can handle a wide range of designs which are then considered and selected through designer intervention. Optimisation methods attempt to replace the designer intervention by employing a mechanism to reduce the number of designs to a single 'best' solution. The approach taken by the majority of optimisation systems is to describe the ship design process in a numerical form. This model of the design process is then used to obtain a 'best' solution through the application of numerical techniques to find a solution that maximises some overall measure of merit. Optimisation based approaches have been proposed for many marine design tools [Nowacki 2009b].

Simple optimisation based approaches employ a single-objective. [Keane et al. 1991] presents a collection of general purpose single-objective optimisation procedures to find the minimum resistance given a number of constrains, including stability and structure. For more complex problems the designer must adopt multi-objective optimisation methods. Application of these approaches within the marine field can be found in [Sen and Bari 1984; Brown and Salcedo 2003; Mierzwicki 2003; Peri and Campana 2003; Brown and Mierzwicki 2004; Parsons 2004]. Of particular interest are [Brown and Mierzwicki 2004] and [Mierzwicki 2003] who incorporate risk analysis into the ship design process. The multi-objective optimisation Brown and Mierzwicki present is used to assess effectiveness, cost and risk concurrently. [Sen and Bari 1984] apply optimisation methods to the design of a replacement inland waterway fleet rather than just a single ship. In addition to exploring a range of ship solutions, Sen and Bari show how goal programming optimisation can be used by the designer to explore the impact of different constrains upon the solution. [Barone and Bertorello 2004] demonstrate the application of multi-criteria optimisation techniques in the design of a non-conventional trimaran hullform.

[9] Both in terms of a range of hullform styles that are of interest to the designer and the set of requirements (or drivers) relevant in a particular design study.

The numerical optimisation techniques described in the preceding paragraph performed poorly if the design space is non-linear and so care is required in defining the design space. Alternatively, there has been a large amount of recent development of other techniques better able to cope with non-linearity, such as Genetic Algorithms (GA). A general introduction to the use of GA in design is given in [Bentley 1999]. A variety of research has been conducted recently on the utility of GA for optimisation in the ship design process, this research is extensively discussed in [Vasudevan 2008]. Researchers have also used GA to conduct cost-benefit analysis [Brown and Thomas 1998; Brown and Salcedo 2003]. Recent research at UCL has explored the utility of the GA as a mechanism for exploring the Pareto front [Vasudevan and Rusling 2006; Vasudevan 2008]. A recent UCL MSc has proposed human guided GA as a mechanism for exploring novel ship design [Smith 2004].

The principal drawback with optimisation based techniques is the difficulty in specifying an objective function or functions. The objective function provides the goal for the method to optimise against. Section 2.2 of this report describes the difficulties of ship concept design, these difficulties result in the objective functions being complex and hard to define. Multi-objective optimisation methods have the additional complication of determining appropriate weightings between the different functions of interest. The discussion of [Keane et al. 1991] provides a frank exploration of the limits of optimisation; in which Brown [1991] and Andrews [1991] comment on the difficulty of determining the objective function especially when the uncertainties inherent within the early stage of the design process are considered.

Such difficulties were experienced while work was undertaken by the candidate to link a ship design software tool (Paramarine) with a generic optimisation/design automation software (modeFRONTIER) as outlined in [Cooper et al. 2007][10]. An initial goal had been to include an optimisation approach able to assess and improve both the vessel's characteristics and its configuration. However, the substantial difficulties of defining a clear objective function were discovered early in the project and a decision made to refocus work on developing a tool better able to assist in exploring the design space. Development of this tool and approach continues [Horner 2009].

The difficulty of defining an objective function is further complicated by the numerous non-numerical ship characteristics. Examples of non-numerical ship characteristics include the layout and ship superstructure style[11]. Andrews [1991] comments in the discussion of [Keane et al. 1991] highlights the dangers in relying upon "black-box" design systems, such as optimisation, due to the problems of trying to express non-numerical ship characteristics in a numerical optimisation structure. In his critique of systems engineering Rydill [1969]

[10]This paper is duplicated as Appendix B.

[11]The central position of layout within the design process is discussed by Andrews within [Andrews 1984]; this discussion is brought up to date in [Andrews 2003a]. A discussion on the styling of warships focusing on the layout of topside structure and systems is presented in [Bayliss 2003]. The role of aesthetics in topside configuration is discussed within [Donnelly 1985].

comments on the dangers inherent for ship design in solely adopting a single numerical solution strategy to the detriment of other important characteristics.

One further argument against optimisation methods are presented by van Oers et al. [2008] who argue that the addition of new constraints radically alters the solutions that are 'best' which renders many of the existing solution unacceptable. They demonstrate that by retaining a substantial number of non-optimal but feasible designs they can better manage the addition of new constraints after the optimisation process has been completed. Two important recommendation were:

- "The designer should consider *all feasible designs*, when selecting designs best reflecting the current set of priorities."
- "Considering all feasible designs allows the incorporation of *additional knowledge a posteriori*, i.e., afterwards during selection instead of interactively during optimisation... Moreover, including knowledge a posteriori also limits the influence of erroneous priorities; establishing their consequences and revising them becomes almost instantaneous as the designs are already available..."

3.2.4 Decision Making Based Approaches

Decision making based ship concept design approaches operate on the premise that decision are initially based upon emerging data which is then reinforced through additional design work. Decision making approaches can be separated into 'Decision Based Design' as proposed by [Mistree et al. 1990] and 'Multiple Criteria Decision Making' as advanced by [Sen 1991].[12]

Decision Based Design applies system engineering[13] to the overall design process. [Mistree et al. 1990; Bras et al. 1990] develop a generic model of the design process, the 'Decision Support Problem Technique', which is stated to enable the designer to model and understand the design process for a given system. Other work employing Decision Based Design includes a hybrid agent set-based conceptual ship design approach [Parsons et al. 1999]. This approach is driven by a decision making process which frames the design process inside a 'market place'; different design elements supply and demand certain characteristics, with the market place acting to produce a balanced solution. One simple but important tool that can be applied to examine the design, analysis and management of complex systems is the Design Structure Matrix (DSM). The DSM facilitates Decision Based Design as it enables the designer to model, visualise, and analyse dependencies among system

[12] This separation was proposed within [Dicks 2000].

[13] As highlighted in Section 2.3.5, systems engineering relies upon the assumption that the important issue in the engineering design process is the interfaces between the different design elements. While not denying Systems engineering's utility as a project management approach, [van Griethuysen 2000] provides an important critique of systems engineering which explores the limits of systems engineering, this assessment is reinforced by Andrews within [Andrews 2003a]. A further discussion is that between Gates [2003] and Andrews in the discussion of [Andrews 2003a].

elements. This also exposes dependencies between design activities allowing them to be re-sequenced thus avoiding the need to revisit earlier design activities. Applications of the DSM to ship design problems includes [Tan and Bligh 1998] and [Laverghetta and Brown 1999]—as shown in Figure 3.1.

		1	2	3	4	5	6	7
General Arrangement Drawings	1	0	1	1	0	0	1	1
Area/Volume Report	2	1	0	0	0	0	1	1
Personnel Access Study	3	1	1	0	0	0	1	0
Midship Section	4	1	0	0	0	1	0	0
Strength Calculations	5	0	0	0	1	0	0	0
Machinery Arrangement Drawings	6	1	1	0	0	0	0	1
Endurance Fuel Calculations	7	0	1	0	0	0	1	0

Figure 3.1: Example Design Structure Matrix, from [Laverghetta and Brown 1999]

[Sen 1991] describes the application of Multiple Criteria Decision Making to marine design problems. Multiple Criteria Decision Making is composed of two different facets: the development of alternative designs [Multiple Objective Decision Making] and the selection of a solution from a range of alternative designs [Multiple Attribute Decision Making]. Other work has explored applying 'decomposition and reuse' within the ship design process [Tan and Sen 2001]. Their work explored using decomposition to partition an overall design problem into a number of sub-problems that can be tackled sequentially. The hypergraph partitioning approach they utilise minimises the number of connection between sub-problems. As a result the overall design process can be restructured to remove a number of 'tedious and often iterative mathematical procedures' [Tan and Sen 2001]. [Karayannis and Molland 2001] provides an example of a decision making model suitable for generating and selecting a robust design for high speed ferries using a Taguchi-type approach built upon their earlier CEM based design tool [Molland and Karayannis 1997]. The decision support model proposed by Erikstad [1996] also shares many characteristics with multiple criteria decision making.

Gonzalez-Zugasti et al. [2007] have recently presented a novel decision making method to assess the potential of different product platforms to fulfil a given mission. Their approach models the different through life platform investment decisions (e.g. fund prototype, fund design phases, buy ships, etc.) as a tree structure. By assigning both costs and probabilities of success at each decision making stage the relative utility of different platform concepts can be compared. While, [Gonzalez-Zugasti et al. 2007] provides an example demonstrating the methods utility in informing a decision between three hullforms the actual task of designing and assessing these alternatives is beyond the scope of their research.

Both Decision Based Design and Multiple Criteria Decision Making aim to promote a more comprehensive understanding of the design process, by enabling the designer to consider the overall design process from an objective perspective. This can be contrasted with the normal subjective case where the designer is part of the design process and so may not be able to impartially assess the most effective methodology to apply. The designer should be able to tailor the design process so he/she is better able to resolve the particular ship design problem[14]. However, for the early concept stage of the design process where the solution is unknown and the requirements are unclear[15] the applicability of these approaches must be questioned. Decision Based Design and Multiple Criteria Decision Making both explore the design process, however decisions on style grossly impact upon the structure of that process. Therefore, these approaches are of more use later in the design process, when the solution type is well understood, and they can then be applied to streamline the downstream design process.

3.2.5 Artificial Intelligence Based Approaches

Artificial intelligence based ship concept design approaches cover a range of methods which attempt to simulate the intelligence of the designer[16]. This topic, termed by its practitioners as machine intelligence, is undergoing much development at present. Two topics from this field are considered in some depth for the ship design problem: Expert Systems and Neural Networks.

Expert systems are a category of design systems which utilise a store of previous design experience to suggest the most appropriate course during the design process. Such approaches store past designs which are then retrieved if they exhibit features which are "similar to" the current design problem. These similar designs are then provided to the designer as suggested solutions. [Park and Storch 2002] provide a summary of the use of expert systems within the ship design field (spanning concept, feasibility, functional and detailed design). A number of authors have explored the use of expert systems for ship concept design [Duffy and MacCallum 1989; Welsh et al. 1990; Park and Storch 2002; Delatte and Butler 2003; Helvacioglu and Insel 2005].

An expert system has three core components: a knowledge base containing the ship design information, an inference engine which retrieves the design solutions that match the design problem, and a user interface which enables the designer to 'drive' the inference engine. Welsh et al. [1990] demonstrate an expert system—INCODES—containing these components tailored to container ship design. Duffy and MacCallum [1989] presented an exploration of how designers of different experience make use of an expert system based ship design tool. They went on to describe the ability of their tool—DESIGNER—to model

[14]The tailoring of the design process can be seen in the different approaches taken by naval architects when designing different type of vessels. A monohull warship may be sized to give an estimation of gross volume, an assumed depth can then be used to determine draught and hence beam and length [van Griethuysen 1992, 1993]. Whereas, for a catamaran passenger ferry a different set of relationship driven by the required vehicle and passenger deck area may be better suited to generating the design [Molland et al. 2003].

[15]And, to some extent, still malleable.

[16]In terms of both the designer's expert knowledge and their decision making ability, as described in [Simon 1981].

uncertainties within the design process through assigning a probability distributions to design variables. Expert systems featuring hierarchical decomposition of the ship geometric elements have been developed allowing different configurations to be examined [Helvacioglu and Insel 2005]. Finally, Delatte and Butler [2003] proposes an object-oriented case based reasoning system as a potential ship and submarine design system.

Expert systems are by their very nature backward looking; they are dependent upon a suitable store of data and are therefore limited to ‘type’ ships. The utility of the expert system with flexible layout capabilities for the investigation of novel configurations is questioned by Pawling [2007]. This would be a significant barrier to the application of expert systems to the design of ships with novel hullforms as the layout is an important determining factor when selecting the appropriate hullform topology.

Neural networks are composed of a group or groups of physically connected or functionally associated neurons, i.e. nodes that control the passage of a signal through the network. The nervous system of many animals is an example of a biological neural network. Artificial neural networks attempt to replicate some properties of biological neural networks. Artificial neural networks employ interconnected groups of artificial neurons that use a mathematical or computational model for information processing. Artificial neural networks are potentially best implemented as adaptive systems that are then trained to perform a given task; a wide range of learning approaches are said to be used by neural networks. Differing network topologies can be employed to alter the system’s capabilities.

Neural networks have been applied to ship concept design by a number of researchers [Ray 1998; Clausen et al. 2001; Cocodia 2005; Maroju et al. 2006]. Clausen et al. [2001] have explored the application of a neural network, trained using data from a commercial source, to select dimensions of a container ship based upon the input of cargo capacity. However, the majority of applications of neural networks relate to the prediction of vessel characteristics. Maroju et al. [2006] demonstrated a hydrodynamic performance prediction tool which utilised artificial neural networks to determine performance levels for hullforms. Similarly, Cocodia [2005] demonstrates a similar artificial neural network based approach to the problem of cost estimation of floating offshore structures. Ray [1998] draws attention to the potential to encapsulate data within an artificial neural network for use during the ship design process. The potential of neural networks to reduce a data set to a number of weighting and bias values is highlighted. This obscures the original sources of data providing an encapsulated tool. In some instances, such as cost estimation using data obtained from multiple shipyards, this may be desirable. However, other performance areas may benefit from clear links to the original data sources.

Artificial neural networks are similar to expert systems in that they are limited by the data available for the initial training. They are backwards looking so, as with expert systems, are limited in their utility for investigating novel configurations and ship style

[Pawling 2007]. However, they are felt to hold great promise in the area of performance prediction [Erikstad 1996].

3.2.6 Configuration Based Approaches

Configuration based ship concept design approaches employ the three dimensional representational capabilities made possible by modern computers to develop and explore the solution to the ship concept design problem. The importance of considering spatial elements within the design process has been the subject of a long term research effort at UCL [Andrews 1981, 1984, 1986, 1998; Andrews and Dicks 1997; Andrews 2003a]. The work recognised the importance of a holistic approach to a fully integrated ship synthesis that allows the integration of the designer's idiosyncratic stamp upon the design, see Figure 3.2 taken from [Andrews 1984]. The practical outcome of this effort has been the Design Building Block (DBB) approach; a summary of this work and the development leading to the current implementation is presented within [Pawling 2007]. A comprehensive presentation of the range of design investigations to which DBB approach has been applied are given in [Andrews and Pawling 2006].

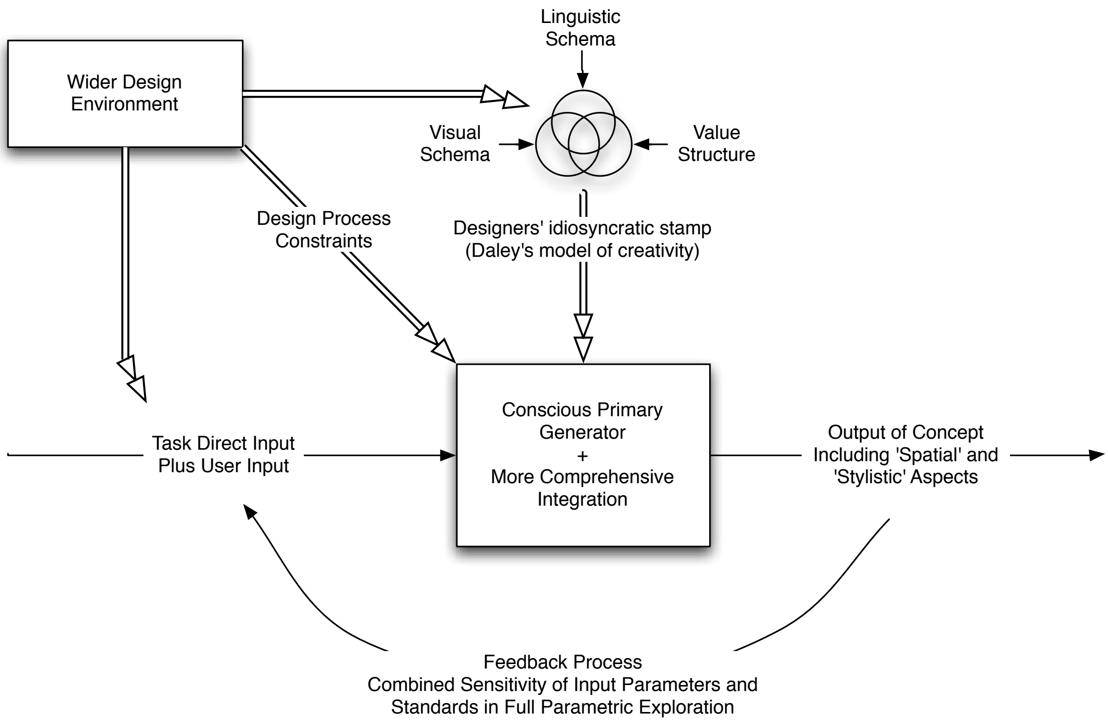


Figure 3.2: Andrews' 'Holistic' Approach to a Fully Integrated Ship Synthesis, from [Andrews 1986]

Andrews [2003a] presents a review of the importance of ship architecture within the ship design process. Andrews highlights the fact most monohull designs are constrained to lie within a relatively narrow range of hullform parameters. Such a large number of constraints do not apply when unconventional hullforms, such as the trimaran, are adopted. However, this new-found freedom results in the size and configuration of the ship's major spaces being a far more important consideration when determining the overall vessel's dimensions and parameters. The configuration based design approach places these issues at the core of the synthesis of a new ship design.

Configuration based design provides a valuable mechanism for developing and exploring new concepts. It enables the designer to explore the design problem in a solution agnostic manner. Creation of a design from a number of functional building blocks should enable the designer to consider radical alternatives. The designer is able to explore solutions to a high level of detail by discretising and developing the design.

The current configuration based design approach makes the designer directly responsible for all decision making which occurs during the design process. The designer works interactively exploring the interaction between configuration and other aspects of the design such as S^5 (as described in Section 2.3.1). In Andrews' Design Building Block approach this involves iteratively manipulate a flexible configurational model of the ship with integrated, comprehensive numerical analysis of the main naval architectural issues using an information rich interactive graphical interface, as illustrated in Figure 3.3. This results in the configuration based approach requiring a large amount of effort to generate a single design. This raises issues when applying configuration based approaches to the very early stages of ship concept design problems, where the designer wishes to explore a wide range of different solutions. The designer must explore each potential configuration type through a discrete synthesis which will take significant time and resources. If this exploration is not undertaken there is the potential for the method to exclude solutions that are better able to satisfy the requirements, thus increasing the amount of compromise and satisficing the designer is forced into accepting.

In addition, Andrews [1986] has described a key part of the methodology as the designer predetermining some elements of each discrete space explored in the solution space, which he characterises as a 'selection of style' step. By forcing the designer to make a conscious decision on style at the outset of the design process a more creative (and potentially innovative) design process is initiated. But this decision on style must preclude certain options from the development of an initial concept. The DBB approach provides the designer with an approach able to perform additional studies exploring the impact of these changes of style. However, potentially substantial amounts of additional work will be required for each major style exploration. As the designer is responsible for all decisions taken in developing each design this will incur a substantial time penalty. While the DBB approach is adaptable and allows the designer to radically alter the configuration and re-balance the ship (hence retaining the designers ability to explore later in the design

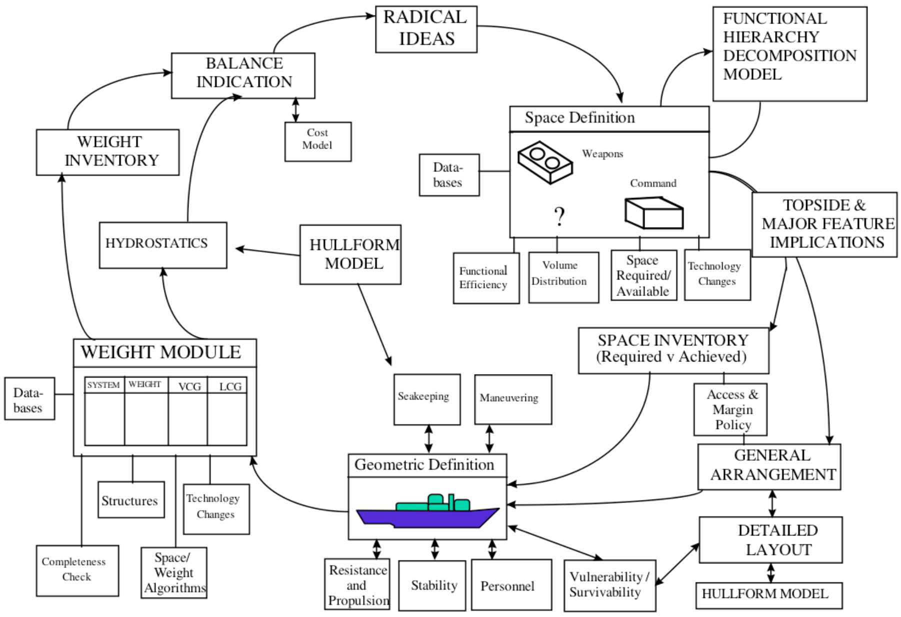


Figure 3.3: The Design Building Block Approach applied to Surface Ship Design Synthesis, from [Andrews and Dicks 1997]

process) the level to which a designer may be willing to revise their design may be limited[17]. Therefore, if the designer is to examine a very large number of widely variety of solutions to determine the most promising candidates, the benefits of adopting a configuration based approach come with a significant increase in time or resources required for the design than in the narrow numerically based approach.

3.2.7 Set Based Approaches

Set based ship concept design approaches advocate the consideration of multiple options concurrently within the design process. Sobek and Ward [1996] highlight this core principle of the set design method: design organisations can benefit from keeping multiple different concepts active until as late as possible in the design process. By keeping more options open longer and developing a number of possible solutions in parallel, the impact of problems emerging later in the design process is minimised. While this will consume more resources in the early stages of the design process, the benefits from selecting a more complete solution will be considerable. By developing a number of different options to a high level of detail, before key decisions are taken, a more complete trade-off can be made. The idea

[17] Chapter 13 of [Lawson 2006] highlights the numerous 'traps' to which designers are susceptible. In the context of ship design Lawson's traps appear particularly relevant: the category trap, where the designer adopts the most common solution; the number trap, where the incorrect application of numerical methods or criteria compromises the overall solution; the puzzle trap, where the designer become preoccupied with self contained interesting sub-problems and fails to grasp the total design problem; and the image trap, where the image of the final product in the mind of the designer differs from that which is possible in the real world.

of deploying more resources earlier is supported by [MoD 2005a] which states that in order to explore options and develop design maturity it may be necessary to allocate a much more significant proportion of a major project's cost to the design stage. Spending of the suggested scale does not currently appear to be undertaken within shipbuilding projects [Robb 2006][18].

Set based approaches have been applied in many different industries including the field of aeronautical and automotive engineering. In the automotive field Toyota developed a set design method which they claim is more effective in producing better solutions [Sobek and Ward 1996]. Applications in aeronautical engineering are discussed in [Bernstein 1998]. Set based design methods have also been applied to ship design problems as part of research conducted at the University of Michigan [Parsons et al. 1999; Singer 2003; Singer et al. 2009; Carlson 2009].

Bernstein [1998] provides one model for how set based design may progress which is shown in Figure 3.4. This model is split into five stages which he describes as follows:

1. "Three specialities (within the design team), or functional groups, are illustrated within the design space (which contains all possible solutions) for a product development problem;

2. First, the specialities expand the number of options which they each consider, establishing a small region of overlap between their design solutions;

3. The specialities work together to expand this region of overlap, increasing the number of solutions which will satisfy all of the product's requirements;

4. The specialities then begin to eliminate options, and the region of overlap shrinks;

5. The solution space is then narrowed until only one design remains, that design being the final solution."

The US Navy has recently applied set based design approaches to perform key trade-off studies as part of the Ship to Shore Connector (SSC) as part of the Landing Craft Air Cushion (LCAC) replacement program [Carlson 2009]. The set based design phase ran from April 2008 to October 2008, during this time the selection of alternatives was delayed for as long as possible to ensure that the impacts of all design studies were sufficiently developed and effectively analysed. By exploring the design space the project team were

[18] [MoD 2005a] sets a target for expenditure on design activities prior to Main Gate of fifteen percent of the systems initial procurement cost. While this level of expenditure may occur in the design of systems where extensive prototyping is possible or that where other research and development will be required (spending on research and development across the UK MoD is significant, [Hartley 2003] report recent values between £2.1 billion and £2.4 billion per year, representing some 9-10% of the total defence budget). However, in the case of ships (such as the UK Type 45 programme) such a large proportion of the initial procurement cost is never incurred unless the concurrent development of combat systems is included (i.e. Principal Anti Air Missile System (PAMMS)) [NAO 2009].

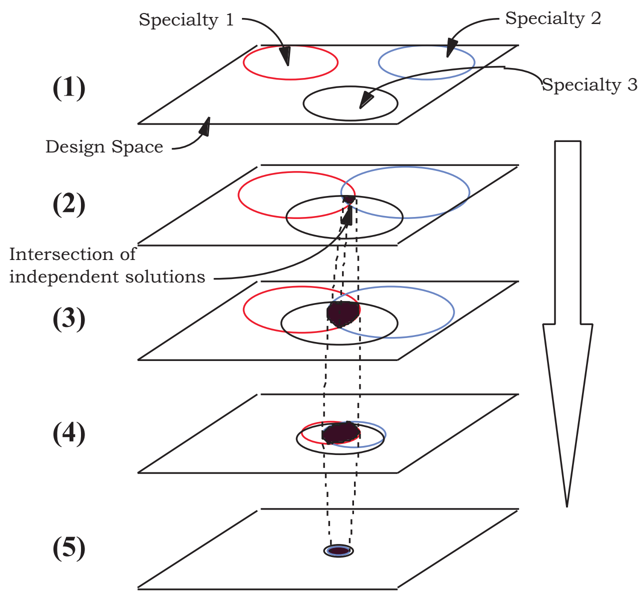


Figure 3.4: Set-Based Concurrent Engineering, from [Bernstein 1998]

able to identify a set of feasible and integrated designs for the SSC craft that spanned a range of capability thresholds of interest. Importantly, the project team reported that the selection of alternatives could occurred at the craft level (as opposed to the system level) and the selection of the baseline design was made on the basis of performance, cost, schedule and risk [Carlson 2009].

This methodology was seen to be useful as it provides a robust mechanism for developing design solutions. The utility of a set based design approach has been demonstrated in engineering design outside the marine field. While the US Navy SSC programme demonstrated the application of set based design principles to a small marine vehicle, for larger vessels a considerably larger number of alternative styles and configurations would occur. However, if only hullform style is addressed Section 2.4.1 showed that different styles can result in radically differing levels of performance which would consequently lead to large differences in the vessel's other systems. In such case the specialists or functional groups areas defined in Figure 3.4 would likely be fragmented by the radically different solutions being considered for each alternative. In this regard it is unclear how the current set based design approach offers substantial benefits for ship design problems such as hullform selection where different styles must be considered.

3.2.8 Decision Making in Ship Concept Design Approaches

The ship concept design approaches presented in this chapter differ in the decision making role the designer adopts. Two extreme design approaches that a designer might adopt could be described as 'involved' (where the designer takes all the decisions, i.e. a glass box) and 'detached' (where the decision making in encapsulated within a tool, i.e. a black box). Most design approaches work as a mix of these extremes since some decision making is usually required from the designer at certain stages of the design process.

Involved design approaches reflect the type of design taught at UCL [Andrews 1986] which in turn reflects the type of design undertaken within the UK Ministry of Defence during the Concept Phase of the ship design process. The configurational approach described in Section 3.2.6 is clearly an involved design approaches, with the designer acting as the creative force in the design process. Computers play a supportive role within involved design approaches, acting as a well integrated calculation tool and data management environment, providing support to the designer, within discrete technical areas, and rapidly performing repetitive tasks. The key benefits of such involved approaches are their high level of flexibility due to all decision making steps being conducted by the designer and the visibility they give to the decisions taken. Involved approaches are able to provide novel solutions particularly when the requirements are hard to elucidate. The ability of the designer to examine and integrate data and information to create knowledge is what provides an design approach with its flexibility.[19]

Detached design approaches rely upon automating the decision making step so it can be completed without designer intervention. This enables detached design approaches to be undertaken rapidly. This speed allows detached design approaches to tackle design problems by rapidly examining a large number of solutions. This ability to rapidly generate a solution (or range of solutions) may improve the dialogue the designer is able to have with the customer, provided both participants have trust in the tool. Detached design approaches are typified by simple numerical optimisation, although other methods (such as expert systems and genetic algorithms) could be included within this category. Optimisation and other detached design based approaches are reliant, at some level, upon a mathematical model of the system. Mathematical models often fail to provide robustness in relation to unexpected inputs, unless significant resources are deployed during their development. The reduction in model robustness results from the requirement to 'hardwire' some of the solution's characteristics. This inherently limits the applicability of tools base upon detached design approaches, precluding design solutions that are novel which can be developed by more sophisticated involved approaches (i.e. the DBB approach). This approach is necessary to constrain the problem enough to enable a model to be both devel-

[19]The knowledge that is gained during the design process tends to be retained on a personal level by the designer or design team. Design documentation tends to report the principal results and, possibly, some background information. Due to the quantity of work undertaken during the design process, the designer is very unlikely to record all decisions and data. However, a design organisation requires information of this type to inform future designs project. Therefore, a design organisation risks losing this information if a designer were to move on. [Ferguson 1992] highlights the problems associated with attempting to retain information on the myriad of decisions which are part of the design process. However, the major choices can and should be recorded, together with the data that informed the designer in making these choices. As stated above the involved approaches seeks to maintain this visibility [Andrews and Pawling 2008].

oped and applied within a detached design approaches; it is immensely difficult producing models suitable for all possible ship types and none have been developed to date. Unfortunately, this results in detached design approaches being very difficult to successfully apply in the concept stage of the ship design process.

Detached approaches also perform poorly when attempting to address either inaccurate information or subjective issues. While powerful when applied to well understood cases, automated systems are susceptible to using inaccurate or inappropriate information which may be used within them. The lack of the wide background knowledge found within human designers results in the automated design systems being unable to detect erroneous results. Appending new data to old models or addressing issues not amenable to the same mathematics (see the critique from [Rydill 1969]) is also both difficult and time-consuming. Subjective issues, such as risk, are often difficult to implement within any highly automated system although research is currently proceeding in this area [Brown and Mierzwicki 2004]. The weakness of detached systems can be mitigated by enabling a designer to trace back through the model to determine how a particular point solution was selected[20]; clearly an important facility if there is concern about the validity of either the solution or the model's information and assumptions as there should be for design disclosure.

Figure 3.5 presents an illustration of where the design approaches described in this section lie on the spectrum of decision making by the tool or the designer.

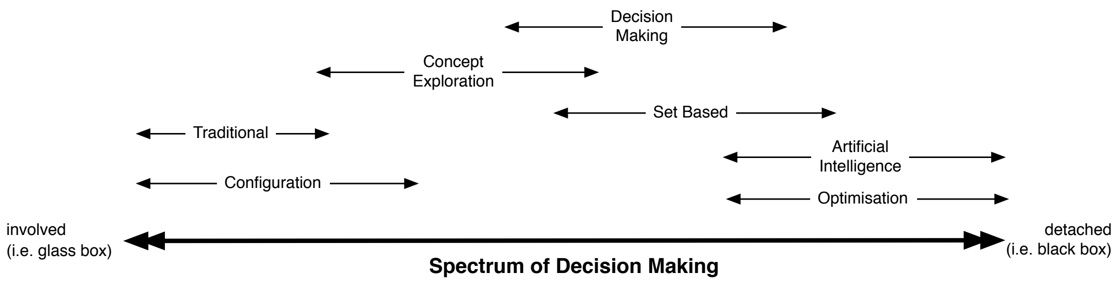


Figure 3.5: The Spectrum of Decision Making in the Ship Design Process

3.3 Two Illustrative Ship Synthesis Methods

This section presents a description of a ship synthesis method encompassing one of the approaches presented in Section 3.2. The term 'ship synthesis method' is deliberately chosen to reinforce the role the method must fulfil; namely the synthesis action that occurs as part of the concept design process. Synthesis refers to the "putting together of parts or

[20]Some automated systems, such as expert systems, already allow the user to examine the basis upon which decisions were made. However, this is only possible in cases where highly numerical characteristics are being considered and such approaches are still unable to assess subjective or architecturally sensitive design drivers.

elements so as to make up a complex whole" [Oxford University Press 2006]. A classical definition of synthesis in the ship design process is the Evans–Buxton–Andrews design spiral shown in Figure 3.6. The spiral was proposed in a ship structural design process by Evans [1959], then developed for ship design by Buxton [1972] where additional detail was included on the tasks undertaken as part of each step. Finally, Andrews [1981] developed the 3-D version shown in Figure 3.6 in order to demonstrate the external constraints which act upon the design process[21]. This model has become widely accepted as providing a coherent representation of the synthesis process.

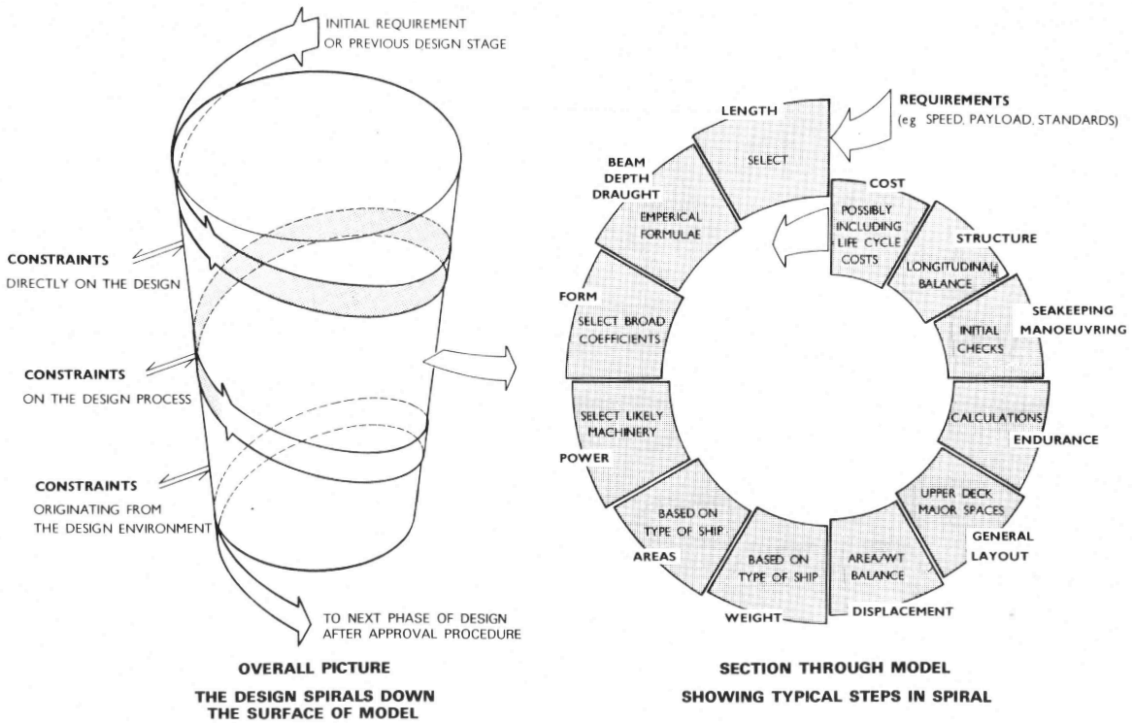
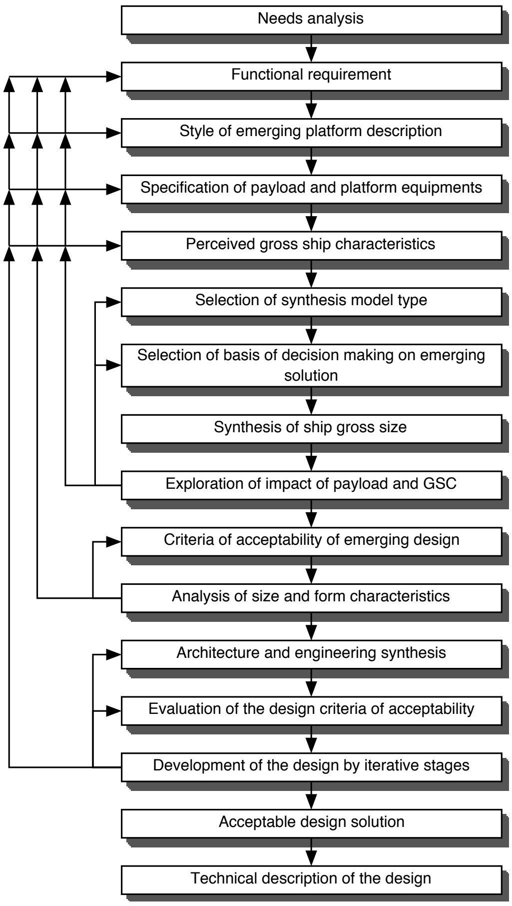


Figure 3.6: Ship Design Spiral, from [Andrews 1981]

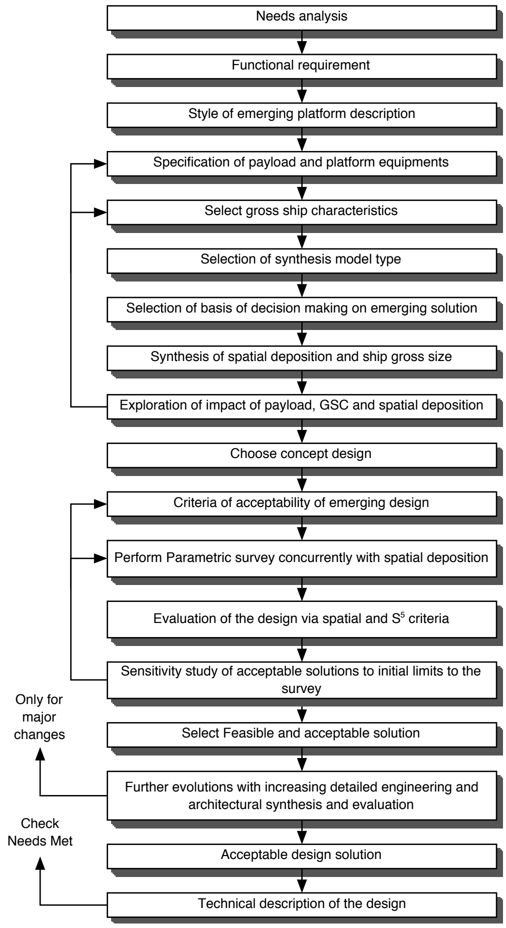
The design spiral suggests the iterative nature of a synthesis to a balanced design from the various elements of the ship. However, this ship sizing and synthesis activity is actually a step occurring within a larger process. The classical model of this process is shown in Figure 3.7a, from [Andrews 1986]. It reflects the design process undertaken by students at UCL and the simple synthesis type of ship design, from Table 3.1. At its core is a synthesis step—"Synthesis of ship gross size"—where the designer balances the design numerically. However, sufficient examination of key design features (such as powering, seakeeping and structure) is conducted at each technical stage (as opposed to the steps shown by Andrews in Figure 3.7 that identify the major decisions required in the overall process) to develop the design. In instances where the designer possesses sufficient experience a 'good guess'

[21] Andrews' version is an adaptation of Mesaiovic's model, as presented in [Watts 1966], modified to form a convergent cone and enables external constraints to be emphasised.

may enable stages to be occasionally skipped [Tan and Bligh 1998]; however, in cases outside their experience this is not possible as would often be the case if multiple hullform styles are to be considered. Design spiral based methods also require considerable time to develop potential designs. Tan and Bligh [1998] highlight the "sequential, iterative, tedious and time-consuming" nature of spiral based ship design methods. The time-consuming nature of setting up a balancing process may inhibit the designer from fully exploring the solution space. Furthermore, the full effect of any modifications to part of the design may take considerable time to be recognised during a design study.



(a) Classical Ship Design Process



(b) Architecturally Integrated Ship Design Process

Figure 3.7: Classical and Architecturally Integrated Ship Design Processes, from [Andrews 1986]

Andrews [1986] also proposed an Architecturally Integrated Initial Synthesis Ship Design Process, which has subsequently been developed into the DBB approach discussed in Section 3.2.6. Andrews' process is able to perform both the simple synthesis, broader synthesis and radical configuration types of ship design. This process is shown in Figure 3.7b; it places far greater importance upon layout during the synthesis stage. Hence, its synthesis step is termed “Synthesis of spatial deposition and ship gross size” (see Figure 3.2).

Both ship design processes shown in Figure 3.7 acknowledge the requirement to select style at the outset of the concept design process. Support for this conclusion can be seen in the case study presented by Andrews and Pawling [2008]. This study clearly identified a design preparation stage where important initial decisions are made. These decisions include the selection of design styles, including the hullform style. The creators of many other design process or systems fail to clearly identify this important decision making step which is therefore being made by default and with the danger that a truncated exploration of options is then performed. Determining style is a key issue the designer must address at the outset of the design process. Choosing an appropriate hullform style is a vital part of design style and is likely to ensure that a design able to satisfy the requirements can be developed rapidly using a minimum of resources.

Opportunities do exist for exploring different hullform variants in the concept phase, particularly during the Concept Exploration stage as highlighted in Section 2.1.1. Pawling [2007] identified a number of converging and diverging steps where different variants are examined, shown in Figure 3.8. Given the capabilities of the DBB approach, as presented in Section 3.2.6, the designer could radically alter the configuration during the design process to the extent that the style of the solution may change. However, the major decisions taken during the design preparation stage and any design work performed form a significant barrier to undertaking this radical step.

In conclusion, the design approaches presented in Section 3.2 are all, in principle, convergent processes (although the set and configuration based approaches encourage the designer to explore divergence design options before converging down to the final option(s) [Rawson 1979]). While this is appropriate for the majority of the design process, where the designer's aim is to develop a single balance design, it is less appropriate at the very start of the design process where the designer is interested in exploring a large variety of potential options in a divergent manner.

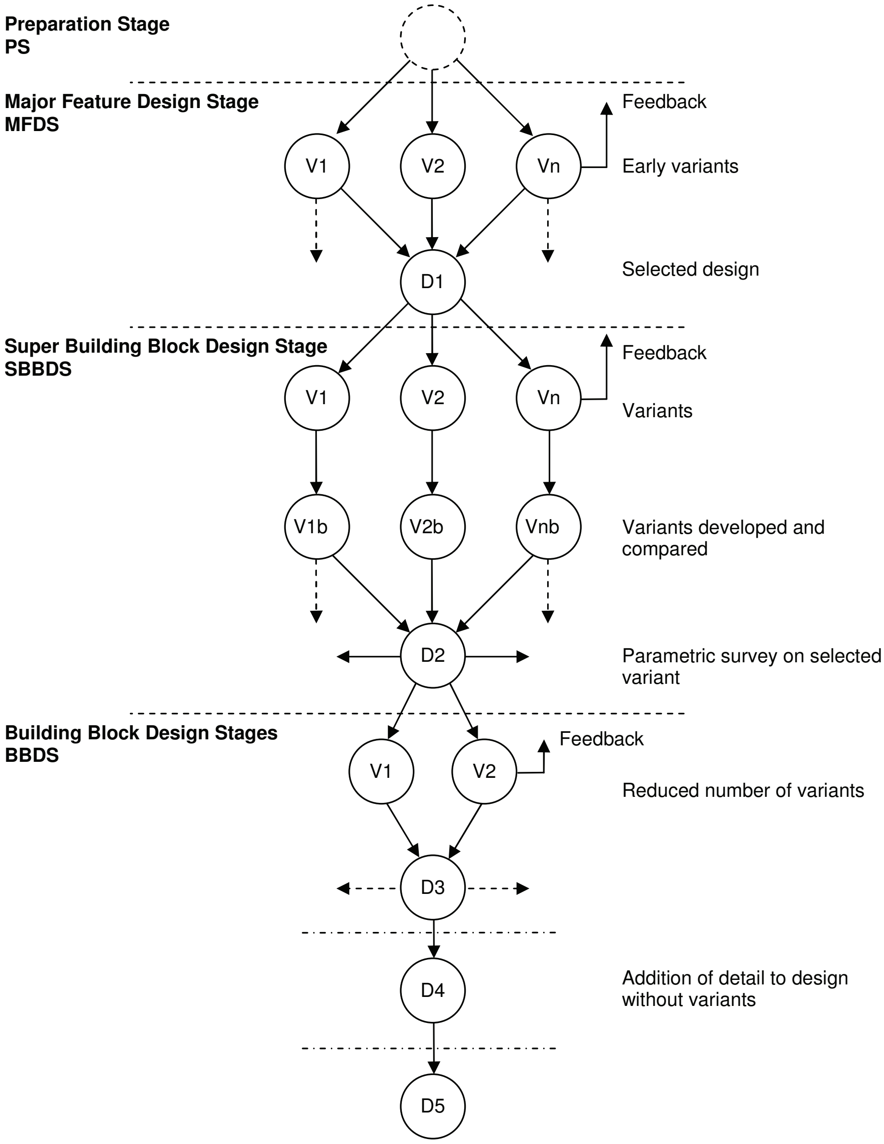


Figure 3.8: Illustrative Diagram showing the Progress of a Design using the Design Building Block Approach, an example study from [Pawling 2007]

3.4 Ship Concept Design Tool Requirements

At this juncture it is useful to consider what features ship designers have previously seen to be required for a concept design tool. Betts [2000] provides a useful checklist for the required capabilities of a warship design tool throughout the concept design process:

1. "Utilise data for assessment of performance, risk and through life cost;
2. Usable by knowledgeable design team;
3. Deal comparably with conventional and unconventional ship concepts;
4. Provide reasonable (preliminary) solutions;
5. Assist communications with design team and all stakeholders, especially those evolving the operational requirement."

While, Andrews [2003b] proposed a list of characteristics desirable in a preliminary ship design approach—both in terms of the process employed and the solutions produced:

1. "Believable solutions, meaning ones that are both technically balanced and descriptive;
2. Coherent solutions, meaning that the dialogue with the operational requirements customer should be more than merely a focus on numerical measures of performance and cost, and should include visual representation;
3. Open methods, in that they are responsive to the issues that matter to the customer/user or capable of being elucidated from the customer or user teams;
4. Revelatory, so likely design drivers are identified early in the design process to aid effective design exploration;
5. Creative, in that options are not closed down by the design method and tool but rather alternatives are fostered."

These two lists of features capture the needs the ship designer requires of their concept design tools, especially at the earliest stages in the design process when the choices (especially that of hullform) have to be addressed. The approaches presented in Section 3.2 have been embodied in tools able to undertake the points outline in Betts' and Andrews' lists (although many tools do not meet all points). But Chapter 2 showed that hullform style exerts a very significant influence upon the performance that a ship solution can achieved. The tools developed to-date, employing the approaches presented in Section 3.2, share a common prerequisite step: namely, a requirement to specify style before utilising the tools. This step is typified in the 'design preparation stage' identified in Section 3.3.

It should be noted that Betts' and Andrews' lists do not state the manner in which decisions should be made within the design process. Involved design methods are seen to be preferable, in that they allow a higher degree of flexibility and can producing a large range of solutions, an essential characteristic for dealing with both conventional and unconventional ship concepts. However, the multitude of decisions, which must be made when using a concept design method based around involved design methods, results in the production of each design being highly time consuming—which is seen to be an impediment to the process of communication between the design team and stakeholders. One example of the significant constrains upon the hullform selection activity is the short duration for particular concept design studies. One example of the time allocated for particular concept design activities are presented in [Lamerton et al. 2008].

While only limited time is allocated to considering different hullform options significant time is required to perform design studies using tool based upon the approaches detailed earlier in this chapter. Representative durations of various different design approaches are presented in Table 3.2. It should be noted that durations in Table 3.2 are indicative of the demonstration of the tools presented in the indicated source. Therefore, these time do not show the tools being applied to either an equivalent problem or a design with a comparable level of detail. However, they do indicate the broad performance of each method. The time needed to undertake design studies using involved design methods are large compare to the time that might be allocated for exploring alternative hullforms, such as those described in [Lamerton et al. 2008]. If the designer is unable to explore these options in the limited time scales outlined by Lamerton et al. [2008] then promising alternative may not be pursued.

Current design approaches have demonstrated a capability to assist the designer in exploring a range of design issues. In particular the DBB approach has shown the capability to assess some style issues that are only likely to be revealed and explored by investigating the vessel's internal configuration [Andrews and Pawling 2006; Pawling 2007]. However, Section 3.3 has highlighted the need for a designer employing a configuration based approach (such as Andrews DBB approach) to synthesise a new design if a radically different alternative is being considered. This forms a considerable barrier that could discourage a designer from altering the initial choices on style, particular hullform style, to fully explore the solution space. A design method or tool able to support hullform selection in the exploratory phase of the ship design process should assist the designer in understanding the customer's needs and hence assist the designer in the dialogue with the customer to elucidate the ship's eventual requirements. It should capture the impact of these evolving requirements on possible solutions. It should enable consideration of different hullform styles and not unduly constrain the designer to a limited selection of options as the methods on the right hand side of Figure 3.5. It must be sufficiently flexible to allow the addition of new information by the designer as it becomes available. It should aim to fulfil Betts' list of preliminary design tool needs and Andrews' list of creative ship solution characteristics.

Table 3.2: Durations of Example Design Studies Adopting Different Approaches

Approach	Involved or Detached	Approximate Duration	Sources
Traditional	Involved	1 week - 2 months	[UCL 2002]
Concept Exploration	Detached	10 minutes[a]	[Eames and Drummond 1977]
Optimisation	Detached	7 hours to 1 day	[Keane et al. 1991; van Oers et al. 2007]
Decision Making	Either	n/a	n/a
Artificial Intelligence	Detached	Hours or days	[van Hees 2003]
Configurational	Involved	1 week	[Andrews 2004; Andrews and Pawling 2007, 2008]
Set Based	Either	1 day	[Parsons et al. 1999; Singer 2003]

[a] For approximately 80,000 options [Eames and Drummond 1977].

Finally, the method should strive to support Andrews taxonomy (in Table 3.1) of different types of ship design novelty from simple development of an existing design through to technologically radical options.

3.5 Conclusions on Current Ship Concept Design Methods and Implementations

Current ship design methods are seen as unable to provide an approach that adequately addresses the hullform style selection issue identified in Chapter 2. This is due to the fundamentally solution centric approach that they adopt arising from the common prerequisite step of specifying styles before developing designs. This approach can be seen to inhibit the earliest exploratory phase of concept design (Concept Exploration), where the designer needs to rapidly explore as wide a range of options as possible. The existing ship design approaches do not appear to provide a mechanism to enable this exploration to be sufficiently wide and quick. Therefore, the next chapter will explore possible alternative approaches from broader engineering design research.

4 Alternative Approaches from Engineering Design Research

4.1 Engineering Design Research - A Framework

The past fifty years have seen a rapid development within the subject of design research—particularly engineering design research and research on design of the built environment. This chapter reviews areas of design research considered relevant to the specific aims of the current research. A more general introduction to engineering design methods is presented in [Birmingham et al. 1996] and [Cross 2000]. This section will draw on a number of sources from beyond the marine field. However, definitions of design from wider design fields appear to correlate with the broad definition of ship design presented earlier (such as those by [Braha and Maimon 1997; Horváth 2004]). They do not relate directly to the ship design problem due to the the unique characteristics of ship design which have been outlined in Section 2.2 on page 39.

This thesis adopts a taxonomy of engineering design research presented in [Horváth 2004] to provide a structure for this chapter. Other approaches are possible which were recently reviewed by Andrews et al. [2006], but the taxonomy provided by Horváth's is seen to be particularly useful. Horváth's taxonomy attempts to determine the underlying order of the current state of the art in Engineering Design Research. Horváth's framework is pictured in Figure 4.1. It decomposes design research into a hierarchy with three elements: categories—domains—trajectories. Categories are the highest level object within the framework, defining broad areas of design research. Categories are then further discretised into domains, then again into trajectories.

The framework classifies categories, and by definition their domains and trajectories, as being either a source, a sink or channel. Source categories provide 'the fundamental mental capacity for engineering design'. The sink category provides the ability to deploy engineering design knowledge in the real world. Finally, channel categories link the source and sink categories, connecting the scientific-theoretical knowledge with pragmatic-technical knowledge.

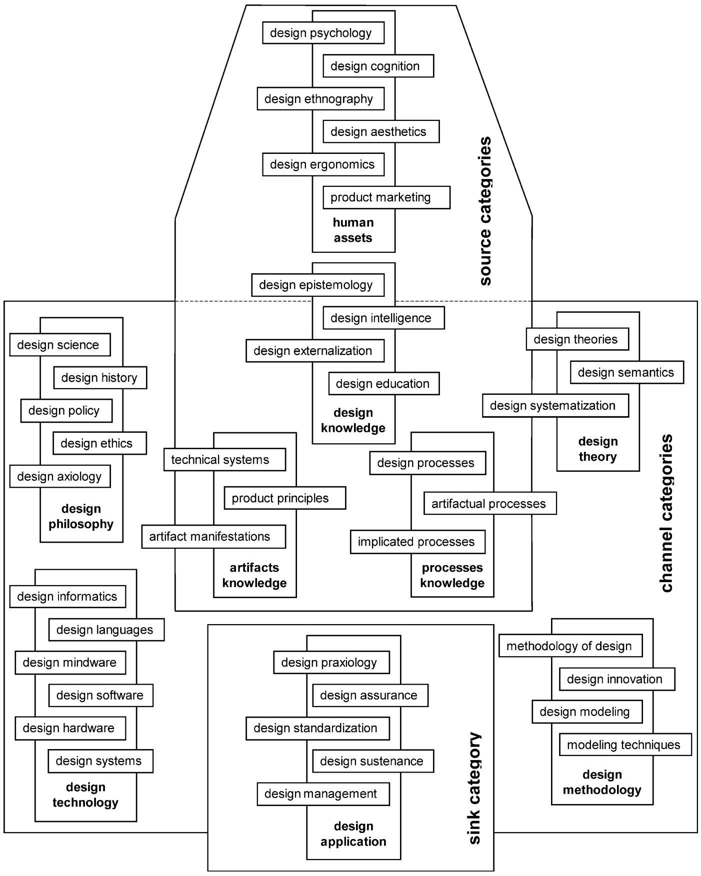


Figure 4.1: A Framework for Engineering Design Research, from [Horváth 2004]; This figure displays the categories and domains within Engineering Design Research

This chapter focuses on three of Horváth's nine categories that are applicable to the problem of early stage ship design: Design Theory, Design Knowledge, and Design Technology. From each category the most important domains will be discussed. Each domain contains a number of trajectories that highlight key trends [Horváth 2004]. The discussion of trajectories has been limited to those which are felt to be applicable to the early stage ship concept design task outlined in Section 2.1. The three key categories are listed in Table 4.1 together with the important domains within each.

4.2 Design Theory

Horváth's category of Design Theory provides a means of recording and improving the development of engineering design in a structured manner. Figure 4.2 shows the overall category showing what Horváth describes as domains and trajectories. Of the three domains that make up the category of Design Theory two are considered to be of interest

Table 4.1: Ship Concept Design Related Categories, adapted from [Horváth 2004]

Category	Domain	Section
Design Theory	Design Theories	4.2.1
	Design Systematisation	4.2.2
Design Knowledge	Design Intelligence	4.3.1
Design Technology	Design Software	4.4.1
	Design Mindware	4.4.2
	Design Systems	4.4.3

with respect to ship concept design: Design Theories and Design Systematisation. Horváth [2004] provides the following definition for the Category of Design Theory:

> "Design theories are dedicated to the organisation of engineering design knowledge beyond the level of craftsmanship."

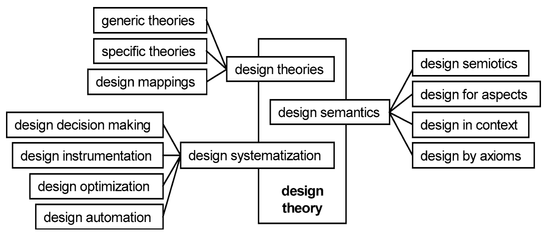


Figure 4.2: Design Theory Category Showing Domains and Trajectories, from [Horváth 2004]

4.2.1 Design Theories

Horváth's domain of Design Theories contains work which attempts to improve the understanding of the structure of the engineering design process. While describing the domain Horváth focuses upon the generic and specific design theories, together with design mappings, which are employed as a means to develop designs.[1] For example, Horváth refers to [Suh 1990, 2001] who describes a specific design method and presents a number of applications of this method. Suh's method—the axiomatic approach to design—attempts to define a limited number of axioms for the "artificial" domain analogous to the axioms defined within the natural sciences.

[1] [Hoset and Erichsen 1997] provide a history of the development of design theory in general and its influence on the design of ships. Further information on the development of design theories in the marine context are presented in the International Marine Design Conference State of the Art Reports [Andrews 1997; Andrews et al. 2006, 2009]. Although there has been a substantial debate over the definition of Design Theories and Methods.

The approaches described by Horváth are underpinned by a limited philosophical approach to the the design process. These methods share a common feature, they suggest that the design process can be regarded as translating a set of requirements into a solution whose properties satisfy the requirements. From this description two spaces can be defined—the solution and performance spaces. These two spaces are linked by a domain theory. An example of a domain theory from the field of ship design is a resistance prediction method; this links the hullform (the solution space) to a resistance value (the performance space).

Domain theories may take many forms, but the simplest rely upon deductive reasoning. Deductive reasoning allows us to apply knowledge of a given rule and a case to conclude a result. In naval architecture the majority of the rules available are obtained from assessments of the performance of solutions. Therefore, it is simple to create a rule from solution to performance. If we define the solution as s and performance as p then we can define the fact as $s \rightarrow p$. A formal logical deductive argument can be constructed which makes use of this rule, as shown in Equation 4.1.[2]

$$\begin{array}{lcl} s & \rightarrow & p \\ s & & \\ \hline p & & \end{array} \tag{4.1}$$

Equation 4.1 states that if a solution is known to exhibit a certain performance $s \rightarrow p$ and we have solution s then we can infer its performance p. This process is shown diagrammatically in Figure 4.3.

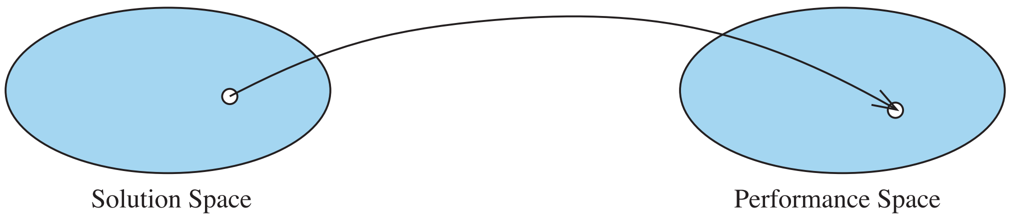


Figure 4.3: Deduction Within the Design Process

It would be more useful for a designer to be able to specify a required performance and obtain a solution through a domain theory, as shown in Figure 4.4.

The argument shown in Figure 4.4 is no longer deduction; a particular set of requirements may lead to a number of solutions. Returning to the logical argument given above if a solution is known to exhibit a certain performance $s \rightarrow p$ and we require a performance p then the solution s should provide this performance. This argument is shown in equa-

[2]March [1984] describes how these domain theories are created as a result of inductive reasoning. This action will be discussed in Section 4.3.1.

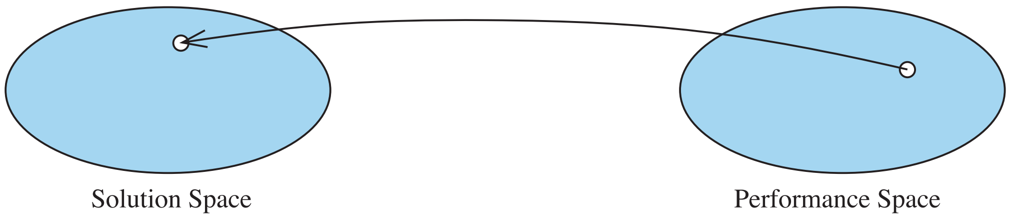


Figure 4.4: Abduction Within the Design Process

tion 4.2 and demonstrates abductive[3] reasoning. There may be more than one solution able to provide the performance required as shown in Figure 4.5.

$$\begin{array}{l} s \;\rightarrow\; p \\ p \\ \hline s \end{array} \tag{4.2}$$

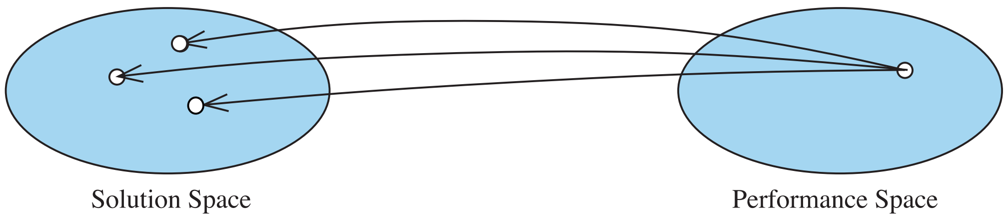


Figure 4.5: Multiple Solutions Obtained by Abduction

Existing ship design processes, as described in Section 3.2 could be seen to contain deductive and abductive steps. For example, Concept Exploration Methods (CEM) employ a purely deductive parallel exploration of the relation between the solution and performance as shown in Figure 4.6. In comparison, the sequential design process undertaken by traditional design methods contains both abductive and deductive steps as shown in Figure 4.7. Many design processes are in-fact a hybrid of these two methods; initial concepts are evaluated in parallel with the most promising solution being further developed sequentially.

[3][Peirce 1958] defines two forms of abductive reasoning: abduction and abductive induction. He differentiates between them through the presence of a prior question: “Abduction is distinguished from abductive induction in not being, properly speaking, experimental, that is, it makes its observations without reference to any previously propounded question, but, on the contrary, itself starts a question, or problematically propounded hypothesis, to explain a surprising observation.” In this case we are referring to abduction in general—representing both types—as the type will vary depending upon the precise context in which the abductive step is made.

More recently, Psillos [2007] presents a summary of more recent definitions of abduction within the philosophy of science. Psillios supplements Peirce’s definition of abduction which as ‘a method of discovering new hypothesis’ with the more recent definition of ‘inference to the best explanation’. These ideas were adapted to design by March [1984].

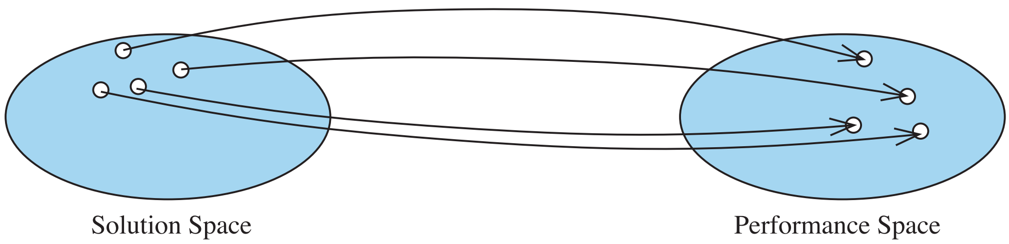


Figure 4.6: A Parallel Concept Exploration Method

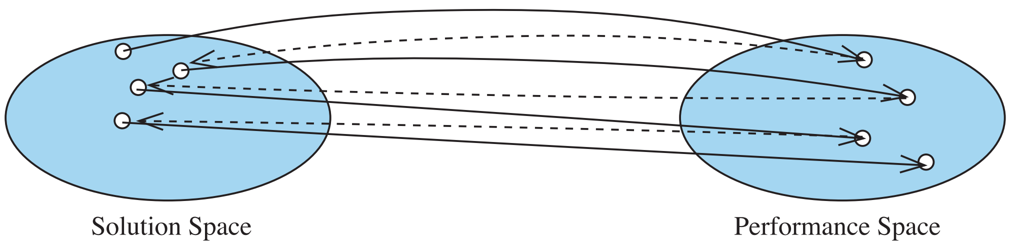


Figure 4.7: A Sequential Concept Exploration Method

This simplistic description of a solution and performance space must be acknowledged as such. The relationship between the performance and solution within an evolving design process is far more complex. [Andrews et al. 2006] provides a comprehensive description of a number of approaches to the philosophy of design which are more suited to the development of "complex" design problems, such as ship design where complexity arises for the reasons outlined in Section 2.2. Furthermore, a more fundamental reason is suggested by Kroes [1998] in that there is an inherent separation between the structure and function of an (artificial) artifact. The requirement for a bridge between these two areas is informed by the reasoning of the designer. Kroes uses the following mapping to illustrate his argument:

structure of the artifact	$\rightarrow$	physical phenomenon with certain properties	$\rightleftharpoons$	properties as a list of specifications	$\leftarrow$	function of the artifact

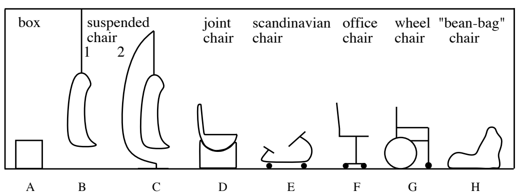
Therefore, function and structure cannot be directly related as a mapping for a complex artifact. Furthermore, Kroes [1998, 2002] goes on to describe these mappings in terms of the dynamic influence the artifact has upon the suitability of the design process used in its own design. Any proposed design method must be able to manage this parallel development process encompassing the structure of the artifact and the function of the artifact. Figures 4.6 and 4.7 illustrate the two mechanisms that can be employed to enable this exploration, either considering a selection of immutable artifacts in parallel or sequentially modifying an artifact to investigate the solution space.

Yoshikawa has proposed General Design Theory (GDT) as a design theory able to explore a selection of immutable artifacts in parallel. GDT provides a mechanism for understanding the relationship between the characteristics and performance of a solution, and hence the mapping between the solution and performance space [Yoshikawa 1979; Reich 1995]. GDT proposes an ideal method for design that utilises ideal knowledge to develop a solution. Ideal knowledge is characterised as the ability to distinguish between any two entities. In this definition, entities represent different solutions and the ability too distinguish is provided by a description of the entities' properties. For the limiting case this leads to a requirement for an infinitely long description to distinguish two entities. Alternatively, for a non-exhaustive set of characteristics defining an acceptable solution there are likely to be an infinite number of potential solutions.

GDT is powerful as it allows the parallel consideration of solutions with radically different topologies. Reich [1995] demonstrates the use of GDT to describe the domain of a topologically different set of objects[4]. In this example eight different objects are defined and then described through their observable properties. The object's characteristics are presented in a set of functional properties[5]. Simple analysis of the complete set of solutions is possible through examining their observable properties[6]. Hence, the properties can be used to sort through the range of possible solutions to determine the subset of solutions that exhibit a required set of properties. Reich's example highlights how this type of approach allows a range of radically different solutions to be assessed. However, the applicability of this approach to highly complex design problems is uncertain.

GDT, as described above, contains a fundamental weakness; it is dependent upon ideal knowledge—defined as knowledge where "one knows all the [objects] and can describe each of them ... without ambiguity" [Reich 1995]. Clearly, for a collection of all possible designs this would lead to an infinitely long list of properties. With this ideal knowledge a designer could use a set of required performance characteristics to directly select a solution (with a complete definition of its properties) that matches the requirements. An incomplete or

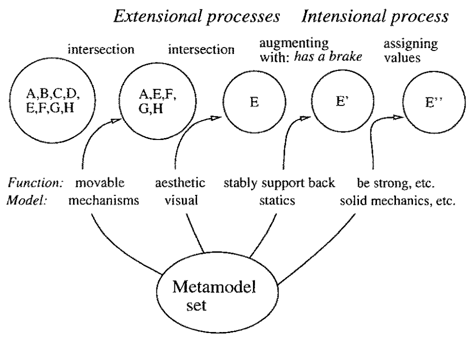
[4][Reich 1995] presents a very simple example which uses chairs to demonstrate GDT. The eight solutions considered are clearly topologically different, as can be seen from the diagram below from [Reich 1995]:



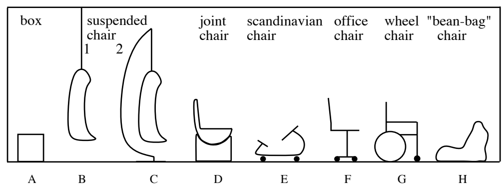
Furthermore, the example uses a limited representation of the artifact (consisting of a small number of attribute-value pairs). [Reich 1995] states that the simplicity of this example does not reflect the scope of GDT. However, the artifacts in this example differs significantly from the physically large, complex, and lived in system described in Section 2.2.1.

[5]Which in a ship could be equated to speed, seakeeping and similar properties.

[6]Which in a ship could be equated to length, beam, draught, depth and similar properties.



(a) Design as a Convergent Process



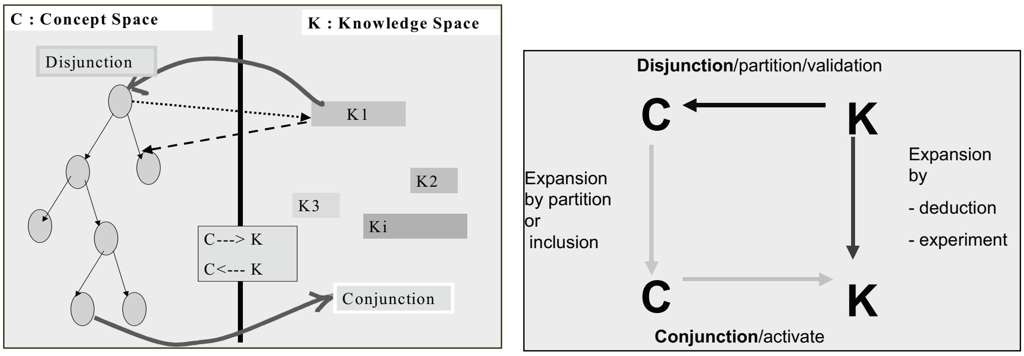
(b) Diagrammatic Representation of the Initial Solutions

Figure 4.8: GDT-Real from [Reich 1995], showing the Extensional and Intensional processes

imprecise list of requirements may result in many solutions satisfying the requirements[7]. In the real world knowledge is limited by the finite amount of time and resources available. This results in an incomplete mapping between the performance and solution spaces. So while GDT can be considered to be Yoshikawa's ideal approach, he has also proposed a related design approach suited to the constrained knowledge and resources found in the real world—GDT-Real [Reich 1995]. Figure 4.8 provides an illustration of the two phases outlined by GDT-Real, an extensional process (where initial solutions are downselected by intersecting their properties with the requirements) and an intensional process (where the remaining solutions are augmented with additional characteristics to fully satisfy the requirements). This figure shows an extensional process where eight initial solutions (A–G) are downselected using two functional demands (movable and aesthetic) until a single solution remains. Next, an intensional process augments the characteristics of the remaining solution (e.g. by adding a brake) finally remaining values are assigned[8]. Yoshikawa [1979] presents a more comprehensive discussion of how General Design Theory could be applied to marine design. A number of the characteristics of GDT-Real could be viewed as being implemented within the CEM's described in Section 3.2.2. Specifically, a CEM could retain the ability of GDT to address topologically different solutions. However, there has not been any exploration of the utility of a GDT-Real based design method in situations where requirements and solutions interact, such as the activity of requirement elucidation discussed in Section 2.3.2.

[7]Furthermore, Andrews [2003a] highlights that the ship is more than the sum of its component part and must encompass some consideration of issues, such as Integrated Logistics Support and Human Factors.

[8]A comparable marine design example is the assessment of a number of hullforms (e.g. Monohull, Trimaran, Catamaran) using extensional processes, such as obtaining the intersection of solutions with low resistance and that are visually aesthetic, to obtain a single solution. This single solution could then be augmented through intensional processes, such as the addition of appendages to provide reduced motions.

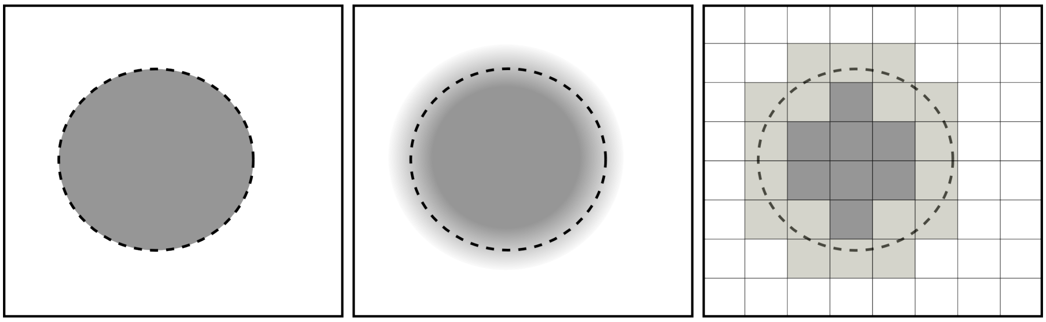


(a) The Dynamics of C-K Theory (b) The Operators of C-K Theory

Figure 4.9: C-K Theory, from [Hatchuel and Weil 2003]

Hatchuel and Weil [2003] present an alternative design theory—C-K theory—that attempts to address weaknesses they perceive in Yoshikawa's general design theory. They feel that Yoshikawa fails to fully recognise the importance of the knowledge "expansion" process that forms a key part of any design process. Further, they question Yoshikawa's reliance on ideal knowledge, obtain through knowledge of all possible objects, which they feel describes a situation which is 'not design'. C-K theory involves an iterative, dynamic process that steps between two spaces: a Concept space (C) and a Knowledge space (K). An illustration of C-K theory as shown in Figure 4.9a. Hatchuel and Weil argue that the concept space can be described in terms of a hierarchical tree of concepts. These concepts are represented by sets for which the axiom of choice has been rejected[9]. A set describing a concept (which Hatchuel and Weil term a concept-set) can be modified by adding or subtracting properties: adding properties partitions the set into subsets; subtracting properties embeds the set into a super-set. Consequently, Hatchuel and Weil [2003] redefine design as an activity where concepts-sets are partitioned or joined (as opposed to searched or explored) to determine a concept-set that contains acceptable options. Hatchuel and Weil also observe that the knowledge space has a less well defined structure. With these two spaces defined, they then describe four operators that are key to developing both concepts and design knowledge, which are shown in Figure 4.9b. This approach is considered to be relevant in that it allows the parallel development of concepts and knowledge. However, by adopting a philosophy that rejects the axiom of choice in defining the set describing concepts, actual options or solutions must belong to the knowledge space. Consequently, the poorly structured knowledge space must be searched for viable solutions, however Hatchuel and Weil fail to provide a robust mechanism for searching and exploring different concepts. This is unfortunately an activity of primary importance for any method intended to provide the basis for a design tool for a ship designer engaged in concept exploration.

[9]The axiom of choice describes the ability to select a single item from a set. By rejecting the axiom of choice the individual items within the set cannot be examined directly.



(a) Set Theory (b) Fuzzy Set Theory (c) Rough Set Theory

Figure 4.10: Comparison of Set Theories

Given the central importance of set representation in both GDT and C-K theory it is appropriate to now review some current developments in the application of set theory to design methods. In particular, fuzzy set and rough set techniques which have both been successfully applied to produce different design tools [Singer 2003; Alisantoso and Khoo 2009]. Fuzzy sets refer to sets whose elements have differing degrees of membership (cf. the binary membership criteria that normally applies to a set) [Zadeh 1965]. Singer [2003] has demonstrated a multi-agent decision making tool for ship design that employs a fuzzy set based representation to improve communication between a group of designers. Rough sets refer to sets where the additional property of indiscernibility is considered. This allows items under consideration to be categorised into those that definitely belong to the set, those not belonging to the set and those items whose membership cannot be determined. A full explanation of rough set theory can be found in [Pawlak and Skowron 2007] while an example of its use in a design context is presented in [Alisantoso and Khoo 2009]. Pawlak and Skowron [2007] contains an useful illustration of the difference between fuzzy and rough set theory: 'In image processing fuzzy set theory refers to the gradualness of gray level, whereas rough set theory is about the size of pixels'. Figure 4.10 demonstrates how a conventional set (Figure 4.10a) could be represented as either a fuzzy set (Figure 4.10b) or a rough set (Figure 4.10c). Both fuzzy and rough set theories could provide useful extensions to either GDT or C-K theory.

This section has explored a number of elements of design theories that may be applicable to the problem identified in Chapter 2. The powerful mathematical and logical tool of set theory has been drawn upon by both Hatchuel and Weil [2003] and Yoshikawa [1979] to form the foundation of their design methods. Fuzzy and rough set methods provide possible extensions to the more fundamental set theories that they employ. In summary, set theory provides the basis of powerful tools for representing concepts in the design process.

4.2.2 Design Systematisation

Two of the four trajectories of Design Systematisation are applicable to the concept design of ships: Design Automation and Design Optimisation.

Design Automation begins with the assumption that engineering design is a computable function. Automation research looks at methods and approaches that facilitate the design process. Developments specific to CAD systems include rule-based and case-base interference mechanisms. Other types of interference mechanisms are described in [Horváth 2004]. An area of present rapid development is the application of evolutionary principles to the generation and optimisation of solutions.

The trajectory of Design Optimisation relates to the activity of improving the design in terms of its performance parameters. Design Optimisation forms an important element of several Design Automation approaches. Much has been written on design optimisation both from a theoretical perspective and with regards to the actual implementation of design methods [Papalambros and Wilde 1988]. However, Section 3.2.3 has shown that there has been little success in applying optimisation to ship concept design. Rydill [1969] ascribes this to the subjective nature of the weightings necessary in multi-criteria methods.

It is unclear if either Design Automation or Design Optimisation would be able to address the problem of requirement elucidation. Both methods experience difficulty in developing suitable goals at the outset of the design process to guide the design system. They also experience difficulties in assessing non-numerical design characteristics such as layout. In this sense, both methods make the assumption that the designer has a clear idea of the role the solution must perform. The examination of ship concept design in Chapter 2 showed how the early stages of the ship design process are an exercise in requirement elucidation with the designer working with the customer to uncover the requirements through exploring the design space. As a consequence optimisation is not an appropriate solution and raises questions about the general suitability of automation methods which take requirements as an input, to aid concept exploration.

4.3 Design Knowledge

Design Knowledge provides the designer with the experience to undertake the design process and the meta-design of the design process itself. The domain and trajectories that form the category of Design Knowledge are shown in Figure 4.11. A single domain from this category was examined—Design Intelligence. Horváth [2004] defines Design Knowledge as:

> "The notion of design knowledge simultaneously means the knowledge about design and the knowledge for (i.e. used in) design."

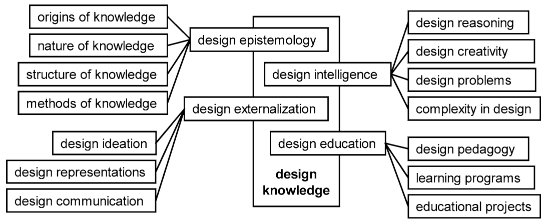


Figure 4.11: Design Knowledge Category Showing Domains and Trajectories, from [Horváth 2004]

4.3.1 Design Intelligence

The domain of design intelligence describes research exploring the ability of the designer to think and learn. Authors discussed by Horváth within this domain of design knowledge include Broadbent [1975], Simon [1981], Daley [1982], March [1984] and Lawson [2006]. A significant portion of the work within this domain draws on research within the areas of philosophy[10] and psychology[11], but it is of critical importance when examining current design processes, specifically those which are heavily dependent upon the intuitive skills possessed by designers. However, this does not preclude attempts to recast the design process in a formal logical context. March [1984] proposes one model of design that describes the accumulation of knowledge within the design process. The model demonstrates the importance of a domain theory within the design process as a mechanism to support the development of a final solution. Domain theories were introduced in Section 4.2.1 where it was shown that simple domain theories represent a mapping between a solution and performance space. An example of a domain theory from the field of ship design is a seakeeping prediction method; this links the hullform (the solution space) to values of seakeeping response (the performance space). Deduction and abduction could then be used to relate solutions to performance and performance to solutions, respectively.

There is one further alternative arrangement for the logical arguments presented in Section 4.2.1—induction. This represents the case where a solution s and its performance p are used to generate a rule $s \rightarrow p$, as shown in Equation 4.3.

$$\frac{(s,p)}{s \rightarrow p} \tag{4.3}$$

[10] A topic covered at length in the research on design within the field of architecture [Broadbent 1975]. [Andrews et al. 2006] contains a summary of the impact of this and other design philosophies upon ship design.

[11] For examples see, Simon's description of the working of the human memory system and its limited ability to handle relatively few 'chunks' of information [Simon 1981] or Broadbent's examination of the numerous psychological studies of designers [Broadbent 1975], although this did primarily focus upon architects which as designers of complex, lived in systems have much in common with ship designers.

Or as a more general case, where information on a number of solutions is available;

$$\frac{(s_1, p_1) \quad (s_2, p_2) \quad \ldots \quad (s_i, p_i)}{s \rightarrow p} \tag{4.4}$$

A design process which includes a mechanism for incorporating an inductive step then enables new knowledge to be incorporated into the design process. By treating the domain theory as the knowledge of a subject, which the designer builds up and employs as part of the design process, induction provides a mechanism that enables the modification of a domain theory due to the unexpected performance of a solution—either the actual solution or a model of the solution which can be considered to be more accurate than just using the domain theory. This important corrective step allows the outcome of the design process to feedback into the design and domain theory[12]. March [1984] proposes the Production–Deduction–Induction (PDI) model to represent a rational design process incorporating induction. The PDI model divides the design process into three steps: deduction, abduction and induction. A version of this model, modified to be consistent with the definitions used within this report, is shown in Figure 4.12.

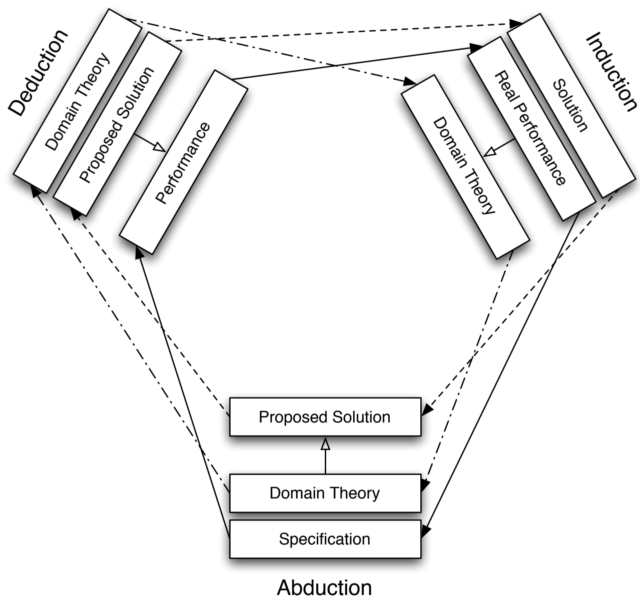


Figure 4.12: March's Model of the Rational Design Process, after [March 1984]

March describes the benefit of adopting the PDI model in [March 1984]; he specifically highlights the benefit of adopting an externalised definition of the inductive, deductive and abductive steps in the design process:

[12]This mirrors the corrective feedback which exists as part of the process of inquiry within the scientific method, and described more generally through the philosophical field of epistemology [Psillos 2007].

> "If internalised personal judgement, experience, and intuition alone are relied upon, the three modes of the PDI-model becomes inextricably entangled and no powerfully sustained use of collective, scientific knowledge is possible. Design will remain more or less personalistic and a matter of opinion, albeit professional. If the design process is externalised and made public, as it evidently must be, for team work to be fully effective, then the three stages of the PDI-model are worth making explicit as much scientific knowledge can be brought to bear on the problem as seems appropriate." [March 1984]

The comparison of alternative hullforms currently relies upon the types of qualitative assessment of characteristics demonstrated in Section 2.4.3. By adopting an externalised PDI model the knowledge contained within the design process is made explicit and, therefore, can be applied more appropriately in the solution of a design problem. Furthermore, examining the design approaches described in Section 3.2, it becomes apparent that current design methods are generally poor at externalising at least one of these steps[13]. Therefore, there would seem to be considerable benefit in adopting an externalised PDI model in the design process to allow the clear definition of inductive, deductive and abductive steps.

A second strand to the domain of design intelligence deals with the designers creativity. Darke [1979] argues that a designer involved in the design of a non-trivial artifact employs some 'key generator' or primary generator which determines an initial configuration of key elements and hence guide the subsequent design, a view supported by Lawson [2006]. Daley [1982] highlights the important role of the designer's interlinked visual, linguistic and value schema. These three schema play a crucial role in the designer's decision making process. Andrews [1998] refers to these combined Darke–Daley inputs as the designer's 'idiosyncratic' influence, illustrated in Figure 4.13. Separate from the user or owner's input, these designer inputs capture the varied contribution the designer makes in forming the solution throughout the design process but especially at the early synthesis stage. Dicks [2000] identifies this important task at a 'Genesis' process that occurs at the outset of the design process, where the "initial leap from blank paper to an unproven sketch to an idea of the solution space" occurs.

[13] For example, when using a Genetic Algorithm (GA) guided design process, such as [Vasudevan 2008], the inductive step of the PDI model would require the performance analysis procedures utilised by the GA to be revised; revision of these procedures will be a non-trivial undertaking.

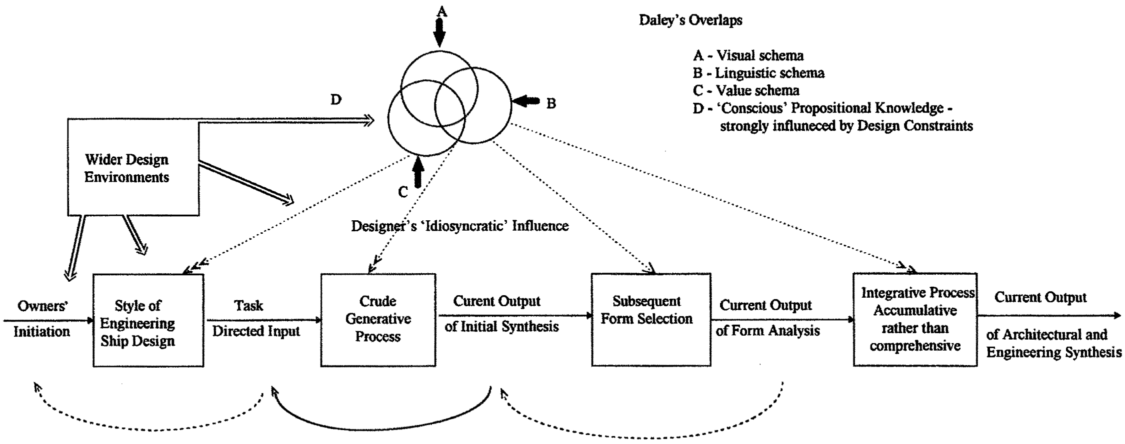


Figure 4.13: Andrews Description of the Traditional, Sequential Ship Design Process Showing the Designers 'Idiosyncratic' Influence, from [Andrews 1998]

4.4 Design Technology

Finally, the category of Design Technology addresses the translation of knowledge discussed in Section 4.3. The Design Technology Category together with its domains and trajectories are shown in Figure 4.14. Three of these domains were examined: Design Mindware, Design Software and Design Systems. Horváth [2004] provides the following definition of Design Technology:

> "[Design technology] is the most characteristic channel category that converts the general knowledge of engineering design to explicit product models and representation"

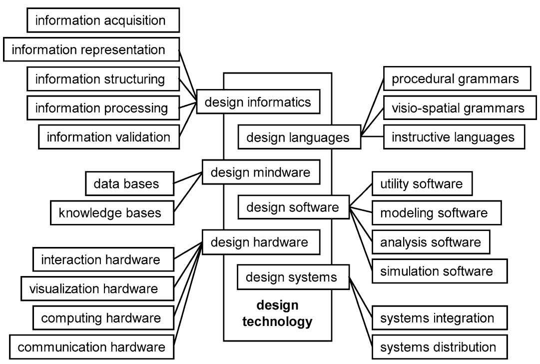


Figure 4.14: Design Technology Category Showing Domains and Trajectories, from [Horváth 2004]

4.4.1 Design Software

The domain of Design Software addressed the use of software to facilitate the design process. There are three key research areas where attempts to develop improved design software take place: software's internal representation of design information; developing the theories and methodologies that underlie design software; and improving software algorithms. Further information on these three areas can be found within the extensive literature published in this field, a summary is presented within [Lee 1999]. However, discussion of these issues must be guided by a broad description of the uses of the software. The uses of Design Software can be categorised into four different groups of software [Horváth 2004]:

- Utility;
- Modelling;
- Analysis;
- Simulation.

Utility software refers to the group of software intended to manage either the design process, design information or both. Some types of utility software attempt to accomplish both of these tasks. Modelling software describes the well-developed group of software that facilitates the geometric definition of the designed item. This may extend to the development of design software able to represent production information. Analysis software provides a range of tools that allow the prediction of the behaviour of a system. Previously such tools have been limited to particular domains, such as structures, however there has been a recent emergence of coupled solvers applicable to many domains [Rees et al. 2001]. The final group—simulation software—can be argued to be acting as a bridge between modelling and analysis software, providing the designer with a radical new design tool. As discussed in Chapter 2, the primary area of interest in the research being presented is the early stage of the design process, before the ship is essentially defined. Therefore, any software that is likely to be developed would belong to the utility software group.

Two programming approaches that may be of interest during the development of utility software in the area of this research are object-oriented and array programming. These approaches provide a means of representing and manipulating arbitrary elements. However, it is first necessary to consider each approaches inturn.

Object-oriented programming uses a collection of objects—individual units—which act upon each other; this can be contrasted with the simple functional or procedural approach taken by traditional programming techniques. Key points of object-oriented programming include Encapsulation, Inheritance, Abstraction, and Polymorphism. Both access to an object's variables and operations upon an object are conducted via methods, this can be likened to specific messages to which an object responds to by modifying its variables, returning information on its current variables or both. Objects also employ Encapsulation to maintain privacy of their internal variables and internal methods. Objects are defined as belonging to a particular class; Inheritance allows an object to duplicate properties, such as variable types and methods, from other classes of objects. Abstraction refers to the ability of object-oriented programming to ignore an object's methods and defer to those of a super-class object. Finally, Polymorphism describes behaviour that varies depending on the object upon which the behaviour is invoked. These key points result in programs written using object oriented languages having improved flexibility and maintainability compared to previous programme structures. Erikstad [1996] provides an example of one application of object-oriented programming in a CEM based ship design system.

A separate programming paradigm is array programming. Array programming allows computations to be expressed at a high-level of abstraction, allowing the manipulation and interrogation of whole sets of data at once. When dealing with large sets of data, array based programming methods provide a concise interface to data sets. Table 4.2 shows an example of the computer code required to perform the addition of two arrays within scalar and array languages. The terse input of the array based language contains obvious advantages in both the generation and maintenance of computer code.

Table 4.2: Examples Pseudocode of Scalar and Array Based Programming Approaches

Scalar language	Array language

for *i* from *0* to *n* by *1* do
  for *j* from *0* to *n* by *1* do
    C[i][j] = A[i][j] + B[i][j];
  next *j*
next *i*
	C = A + B;

These two approaches can be combined to provide a powerful programming language that enables the manipulation and interrogation of a large collection of objects through concise code. By integrating object-oriented programming into array based programming a single command—or message—can be sent to a number of objects simultaneously. Each object will then respond to the method, although different objects may respond in vastly different ways. Further information on object-oriented array based programming can be found in [Mougin and Ducasse 2003].

4.4.2 Design Mindware

The design mindware domain encompasses the structuring and archiving of information. During the design process the designer must make use of a large amount of varied information. This information can be divided into data and knowledge. The storage of both forms of information may be undertaken as part of the design mindware process. However, there is a subtle difference between these two forms of information which impact the storage philosophy adopted. Data pertains to the facts which are known about the subject in question. Knowledge in comparison refers to the set of facts, assumptions and interference rules that pertain to a particular type of design [Erikstad 1996].

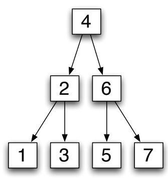
A multitude of different methods are available to the designer to facilitate the management of this information [Atzeni et al. 1999]. In terms of computer-based methods, databases have adopted a central role; many different organisational model options exist for databases: Flat, Hierarchical, Network, Relational, Dimensional, and Object database models. Each has particular strengths and weaknesses, allowing data to be stored in an appropriate structure for different tasks. However, all databases provide a mechanism for the storage and rapid access of large quantities of information. One example of this is the mechanism used in many database systems to perform a search—the B-tree index[14]—this allows n elements to be searched using a number of operations that scales logarithmically with n. Databases can therefore scale efficiently to large data sets.

4.4.3 Design Systems

The final trajectory of design technology is Design Systems. This trajectory addresses research which attempts to integrate disparate tools into a single system. This includes attempts to provide a more well-managed designer led system, either through shared data or, potentially, virtual reality. Some Design System research has extended to systems that are intended to remove or replace the designer, such as automated problem solving and design support systems. The utility of this approach has yet to be properly justified for all but the most basic of design problems.

Attempts to develop an integrated design system are to be commended if the tool developed remains generic in its applicability. The Paramarine ship design software suite [RINA 2003] is an example of a design system currently undergoing substantial development. Paramarine incorporates into a single tool a CAD modelling tool, technical analysis capability[15] and one implementation of the configurational based design approach outlined in Section 3.2.6. In comparison, some other design systems provide tools highly focused

[14] A search method closely related to the B-tree is the self-balancing binary search tree, an analogous method that is not optimised for database applications. The illustration to the right shows a simple binary tree containing objects labelled with some key that is of interest. Given a target value, the search begins at the root node (i.e. 4) and compares the node's value to the target value. If the target value is less than node's value the search then examine the node to the left (i.e. 2). Else if the target value if greater the node to the right is examined (i.e. 6). The search continues until a node matching the target value is found. In the example right searching for the value 5 takes a total three operation (e.g. 4→6→5) where as searching through a list of seven elements could, in the worst case take, seven operations. The height of a balanced binary tree is $\log_2 n$ as the number of nodes on the kth level is given by 2^k. Therefore, the maximum number of operations to find any value will scale with $\log_2 n$. [Atzeni et al. 1999]



[15] Including stability, powering and structures analyses.

upon a single type of solution. While this is useful for certain situations, retaining the potential to explore radical alternatives is a desirable objective especially in the divergent phase of requirement elucidation.

4.5 Conclusions on Alternative Approaches from Engineering Design Research

This discussion of design research applicable to ship concept design has presented a set of key research activities which may prove fundamental for further developing the ship concept design process. The three categories explored—Design Theory, Design Knowledge, and Design Technology—provide the understanding, expertise and practical systems which will enable the development of a design method able to determine the most appropriate hullform style. A number of research domains within these categories were explored to assess the impact of design research on the challenges present in the early stage of ship concept design.

Horváth's domain of Design Theories provides a range of design methods which describe design in terms of a mapping between the solution and its performance. When determining the performance from a solution this mapping is deductive and therefore simple[16] to apply. In comparison, determining the solution from a set of performance targets (i.e. requirements) is shown to be an abductive process and therefore problematic. One design theory—GDT—which features this solution–performance mapping has been considered. GDT allows the design problem to be represented through sets of solutions which enables simple sorting operations to be used to explore the relationship between the performance and possible solutions. Concept Exploration Methods contain a number of similarities to GDT-Real, the implementation of GDT which uses non-ideal knowledge [Reich 1995]. By developing a CEM that takes into account the principles of GDT a design process could be developed that retains GDT's ability to assess solutions with radical topological differences. Horváth [2004], in discussing his domain of Design Systematisation, explains why Design Automation and Design Optimisation are unsuitable for concept design.

From the category of Design Knowledge the domain of Design Intelligence explored the designer's ability to think and learn. Specifically, it explores the accumulation of knowledge and the incorporation of this knowledge into the overall design process through the development and refinement of 'domain theories'. March's Production–Deduction–Induction model was presented (Figure 4.12) and the benefit of externalising the elements of his PDI model were described.

Finally, in the category of Design Technology three domains were described: Design Mindware, Design Software and Design Systems. The examination of the domain of Design

[16] But not necessarily easy, as is the case when attempting to determine a ships hydrodynamic performance [Erikstad 1996; Bertram 2000].

Mindware revealed the range of mechanism's available for the storage of design information, including a broad range of types of databases suited to the storage of different types of information. Similarly, the examination of the domain of Design Software highlighted some systems suitable for developing and manipulating this data; Utility software has been identified as being a key factor in the early stage of the ship design process. Two programming approaches—Object and Array based programming—have been highlighted as being of considerable interest for the development of Utility software. Finally, from the category of Design Systems the current trend of combining disparate tools to form a single integrated system that can be used by the designer has been highlighted.

For the alternative approaches presented in this chapter to be used to improve the design process they have to be incorporated into a suitable design approach. However, before using the conclusions from this section to develop any solution, it is necessary to reassess the precise problem the research is addressing. The next chapter begins with a summary of the design problem—hullform selection during requirement elucidation in the ship concept design process. Next, a design approach is proposed that it is suggested can address this problem. This design approach differs from those found in Chapter 3 and incorporates a number of the alternative approaches considered in the current chapter.

5 A Library Based Ship Concept Design Approach

This chapter presents as an alternative a concept design method employing a Library Based approach. Section 5.1 presents a summary of the key points originating from earlier chapters that lead to justifying such a new approach to the problem posed. Section 5.2 then presents a brief overview of the Library Based approach and highlights its similarities to certain existing design approaches. Next, the assumptions underlying the Library Based approach are described in more detail in Section 5.3. Finally, Section 5.6 presents the hypothesis that needs to be tested in order for the approach to be valid as a design approach applicable to the ship concept phase.

5.1 Summary of the Problem

The three preceding chapters have provided a description of the problems surrounding the selection of hullform at the earliest stages of the ship design process. Chapter 2 identified the concept exploration stage as being a key element in the development of a solution allowing a rapid exploration of potential options. However, difficulties arising from both the complexity of ships and the complexity of the ship design process lead to significant problems in developing a design able to satisfy the emergent performance requirements. An assessment and consideration of ship requirements in the concept design process highlighted their importance in this process; both as a factor driving the design activity but also through the ongoing dialogue by the designer with the requirement owner, and other stakeholders. This is seen to be a consequence of the requirements being heavily influenced by the evolving design definition (i.e. the 'wicked' nature of the problem). The need to address alternative hullform styles is seen to present a challenge as their differing performance characteristics lead to disparities in the extent to which they can individually fulfil the requirements. However, alternative hullform styles must be considered early in the design process to exploit their potential benefits in meeting the emergent need.

Chapter 3 began with a summary of the types of ship design processes. Next, existing ship design approaches able to support these types of ship design processes were highlighted and classified. This examination identified a number of the ship design methods and tools used throughout the design process. The wide range of current ship design approaches were considered to inhibit the designer in their need to rapidly exploring alternative options, such as different hullform styles, at the beginning of the design process. By examining an illustrative ship synthesis method, the inability of these approaches to either explore options with different styles or to do so sufficiently rapidly was identified as a consequence of the need to make a style decision (i.e. a monohull style hullform) before employing a specific design method. While a method could be used a number of times to explore different hullform options this is felt likely to consume significant resources and time, thereby inhibiting the wide exploration deemed appropriate for satisfactory design exploration and requirement elucidation.

Finally, Chapter 4 provided a taxonomic and logical context to engineering design research by highlighting a number of possible alternative approaches that may offer advantages if applied to the early stage of ship design. Initially, the important distinction between sequential and parallel design methods has been addressed. The majority of current methods employ a number of sequential abductive and inductive steps between the solution and performance spaces to explore the design space and incrementally improve a solution. Few methods are considered to provide the designer with the ability to explore many options in parallel. However, parallel methods may provide a better mechanism for exploring the solution space in the early stages of the design process (and hence a better learning mechanism). While design optimisation or design automation have been used successfully to explore specific solution of a specific ship type, neither method appear to provide a coherent mechanism for comparing options with radically different styles. This is particularly true for hullform style where different hullform styles give distinctly different levels of performance. The chapter also highlighted March's [1984] work on the importance of capturing new design knowledge in a form that enables future use. Incorporating a method that allows design knowledge to be accumulated, such as his PDI model, is considered important in any design situation but arguably more so in cases when the initially available design information is sparse. Finally, an examination of design technology highlighted utility software (intended to assist the management of design information or the design process [Horváth 2004]) which is seen as likely to be of importance in assisting the designer early in the design process. Databases and object oriented programming have been investigated as they are seen to provide potential in developing appropriate utility software.

5.2 A Library Based Ship Design Approach: A Potential Solution

From the consideration of current design methods in Chapter 3 it is concluded that they are seen to be difficult to apply to the key problem of hullform selection. It is instructive to consider the process of ship design as analogous to writing a book (given both could be considered to be creative synthesis processes). Thus designing ships with different styles might be seen as akin to writing books of different genres. Someone interested in writing a new book is unlikely to write a number of drafts using every style they are considering then discard the draft romance, mystery and science fiction novels to improve the thriller. Instead, an author might well visit a library and examine books from the catalogue to find prospective styles that may be appropriate. The effectiveness of the library is enhanced by the search and classification mechanisms that are in place. Therefore, there is some potential merit in examining a Library Based approach in the context of ship concept designing, particularly when different styles are of interest. Despite the analogy, it is clear that the aims of the two processes are entirely different.

It is the contention of this thesis that the ability to explore alternative hullforms, seen as an aim of early ship concept work, can be satisfied through a Library Based approach. The Library Based approach to ship design comprises a library of design data that can be rapidly searched to find potential options. In this thesis 'options' are defined as a specific discrete design examined by the designer; for example a single point design for a ship would be one option. Figure 5.1a and 5.1b show an analysis of the relative performance, in terms of run time verses number of options considered, of four different design approaches: brute force, deterministic optimisation, stochastic optimisation and a simple Library Based approach.[1]

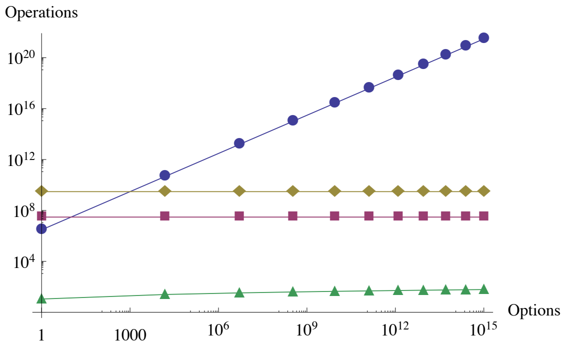
The brute force approach exhaustively assesses all potential options. Deterministic optimisation approaches, such as the method of steepest descent, utilise a simple rule to determine the next solution to be assessed based upon information on the current solution (and possibly previous solutions). Stochastic optimisation approaches employ some probabilistic elements in the solution of an optimisation problem. Finally, the simple Library Based approach is similar to the brute force approach but the values for the options are pre-calculated and stored in a library.

The comparison presented in this section are presented in terms of an estimated number of computational operations that must be performed. This is analogous to the number of low level steps or calculations a computer running the program must perform to evaluating the number of options specified. Due to the large number of variables in the calculation process these times should be regarded as broadly indicative of the likely duration. Actual durations will depend upon the performance of the computer executing the code and the calculation methods employed.

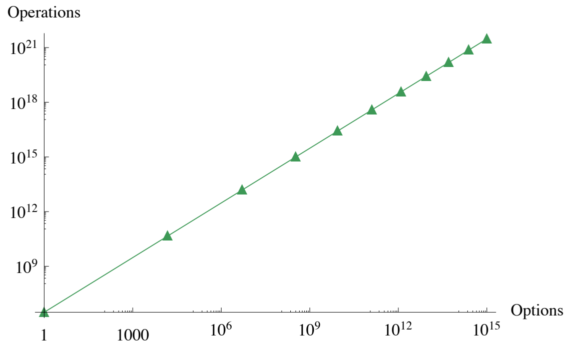
Of the four methods compared the brute force, deterministic optimisation and stochastic optimisation based approaches are methods that conduct all operations on line—with the designer running the tool. In comparison the simple Library Based approach separates

[1]These estimates were developed by formulating a simple parametric relationship describing the actions within each approach. By making a conservative estimate of the time required for each operation it was possible to investigate the total number of options that could be assessed. More importantly this method captures how a Library Based approach scales as the number of options being considered is progressively increased. Appendix C contains full details of the method used in the analysis.

the design task into two stages. The first stage consists of precalculation, creating and analysing a number of options to create a library. This stage could be conducted offline. The second stage consists of the designer examining the options on line, as part of the design process.



(a) Run-time Complexity



(b) Pre-calculation Complexity

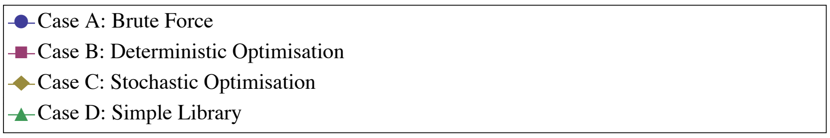


Figure 5.1: Relative Complexity of Brute Force, Deterministic Optimisation, Stochastic Optimisation and a Simple Library Based Approaches for Initial Ship Design Exploration

The above comparison highlights that a simple Library Based approach can be undertaken at a similar execution speed to optimisation based methods. In addition while the optimisation approaches only explore a small number of solutions as they seek out an optimal solution, the simple Library Based approach allows a comprehensive examination of the design space represented by the solutions in the library. This enables the designer to gain considerable insight on why particular options may be unacceptable.

While the simple Library Based approach presented here could be employed, the precalculation step is still highly time-consuming. Therefore, some additional step may be required to develop this approach into a method that retains the ability of the simple Library Based approach to examine multiple solutions while reducing the extent of the number of options in the precalculation step. A high level outline of the proposed approach is presented in Section 5.2.1. Section 5.3 then discusses in more detail the underlying methods and philosophy underpinning this proposed design approach.

5.2.1 Introducing a Library Based Approach

The proposed approach is based upon a limited library of possible design options describing a large number of possible ship designs. This library has to be constructed before the designer begins to search for potential options. The designer is then able to rapidly filter the options in the library to find those that satisfy the current design requirements. Inspecting the remaining options gives information on the consequences of adoption one of a range of acceptable styles. This allows the designer (and hence the stakeholders) to gain a better understanding of the impact of any requirement upon the styles available to provide potential ship solutions.

A number of different ship synthesis methods presented in Section 3.2 can be used to develop the library. For example the design procedure used for the major postgraduate ship design module at UCL [UCL 2002], or similar ship synthesis methods, could be drawn upon to create a large number of potential options to populate the library. After generating these options, the characteristics and performance of each option can be found and stored within the library, avoiding some of the time-consuming calculations that need to be performed once the designer proceeds to explore potential options.

The initial library has to be broad enough to contain an array of options that might be of interest to the designer. However, it is apparent that the number of options within the library will quickly grow and soon become unmanageable. Thus if a ship is synthesised from ten input variables, each with ten possible values, this implies a theoretical total of 10^{10} options [Erikstad 1994]. Yoshikawa's General Design Theory, highlighted in Section 4.2.1, represents a extreme implementation of this approach in the form of a selection method requiring ideal knowledge. However, this requires an infinitely large library combined with an unlimited processing ability. Therefore, some other mechanism is required, enabling a wider range design options to be considered.

One approach is to implement a process of decomposition and then down select. This would reduce the number of options that need to be stored within the library. For example, by decomposing each ship option into a number of sub-options, which are then stored in the library (in place of the ship option), and then subsequently combining these sub-options, a far larger set of possible whole ship options—termed 'combined options'—could be produced. Taking the results presented in Figure 5.1 a similar approach could be adopted to show how the complexity of the approach changes when adopting a decomposition, down selection and combination approach. This comparison is presented in Figure 5.2 and shows the case (Case E) where the ship options have been decomposed into three equally sized sets of sub-options so that the total number of operations reduces (typically 10^{12} c.f. 10^{21}).

Conceptually a combination operation could, if formulated carefully, be applied to a number of different sub-options in a manner that should be blind to the style of the overall ship option. The options resulting from a combination operation would then have characteristics or performances dependent on the sub-options. For some characteristics, the methods required to determine them should be simple to apply. For example, an assessment of the combined ship weight or volume for a number of sub-options (representing specific sub-systems in the ship) could quickly be determined for the combined option. However, it is recognised that this approach simplifies the combination of different sub-options and

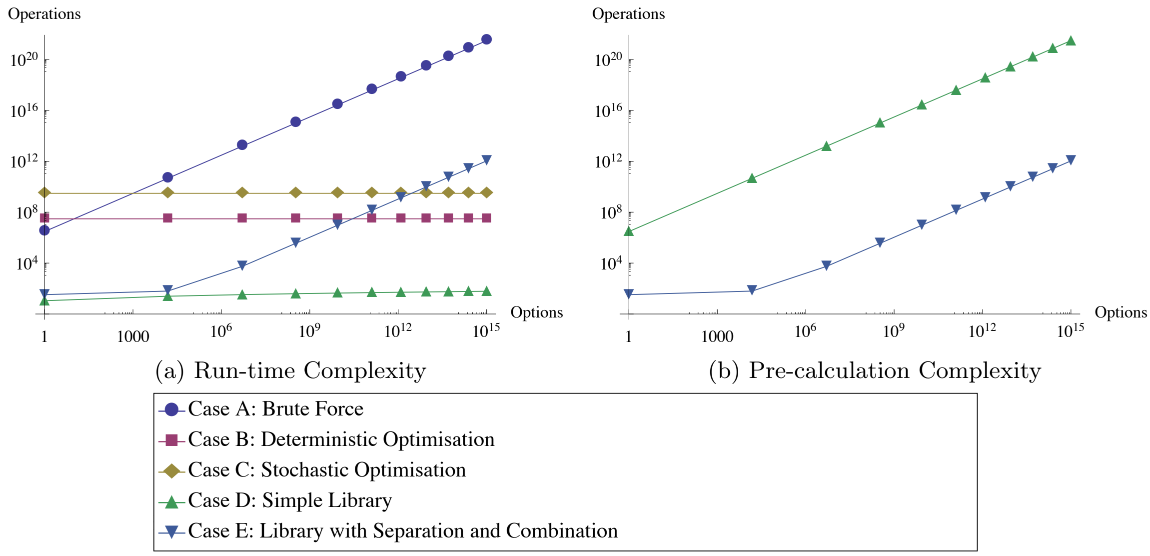


Figure 5.2: Relative Complexity including Library Based Approach with Decomposition, Down Selection and Combination

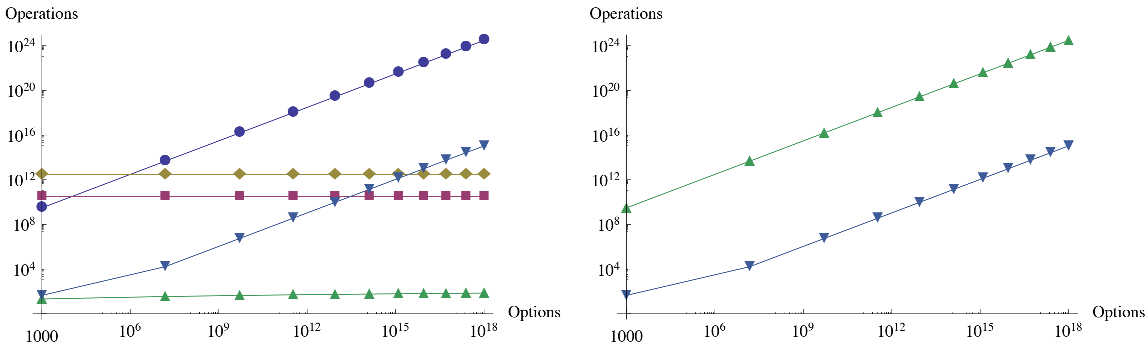
risks failing to capture the real impact that combining two or more different sub-options has upon the combined option's characteristics. For example, the total propulsive efficiency would depend upon several elements of the combined option and also be highly dependent upon sub-option styles. Improved prediction tools, targeted at specific aspects, could then partially offset any possible loss of accuracy[2]. Furthermore, this method could then feed into the remainder of the design process, where other design methods and tools might better capture the impact of effects arising from the interaction of options that are of particular interest.

It is worth noting that the characteristics of acceptable options arising from a certain combination of styles may radically differ as the design's style is changed[3]. This means optimisation based approaches, which focus on the characteristics of the solution, would be unable to switch easily between styles. Figure 5.2 showed relative complexity for the case where only a single style was considered. If a number of styles were considered for each of the sets of sub-options, then the run times for the optimisation based approaches would increase more rapidly than that of the Library Based approach, as is shown in Figure 5.3[4].

[2]Section 3.2.5 highlights a number of artificial intelligence based ship design approaches that could be applied to rapidly predict performance, if a suitable set of data was to be available to train the system.

[3]For example, a characteristic such as overall length varies significantly with different hullform styles, as demonstrated in the comparison of Monohull and SWATH hullforms conducted by Kennell et al. [1985] that has already been discussed in Section 2.4.2.

[4]These figures demonstrate the case where ten styles are considered for each of the three functional group. For the optimisation based approaches this has been represented as a requirement to run the optimisation model 1000 times to deal with each potential combination of styles. For the brute force and simple Library Based methods the number of options has been increased to include the options representing the different styles. Finally, the increases in the size of the library (with separation and



(a) Run-time Complexity

(b) Pre-calculation Complexity

- Case A: Brute Force
- Case B: Deterministic Optimisation
- Case C: Stochastic Optimisation
- Case D: Simple Library
- Case E: Library with Separation and Combination

Figure 5.3: Relative Complexity with an Increased Number of Styles

The decision upon the type of decomposition to employ is of central importance to this approach. A number of different existing decompositions approaches have been summarised in Section 2.3.5. For a method providing the designer with a means of evaluating different hullforms, the functional group breakdown adopted by Andrews and Dicks [1997] for surface ships provides a number of advantages, as detailed in [Andrews et al. 1996]: it helps foster innovation; it exposes interrelations between functional groups; and it reveals the relative impact of specific requirements on functional groups. Thus, each option of the ship design is decomposed into those four functional groups: Float, Move, Operation (or Fight) and Infrastructure.

As a large number of variables within any design will be continuous, it is recognised that solutions will exist between both the options within the library and the different combined options (as these are simply composed from sub-options selected from a discrete library). Additionally, there will be limits on the extent of the solution space that sub-options within the library can represent. These two factors are a significant limitation to a Library Based approach and while there is scope to extend the method to enable other options to be considered (to cover either additional options between existing points in the library or to extent the coverage at the extremes of the existing library), for simplicity, this additional feature has not been developed further in this realisation of the approach.

The options from the library could be filtered via a number of different search mechanisms already employed by the database tools discussed in Section 4.4.1. The power and speed of current search techniques should be familiar to any user of typical Internet search engines

combination) has been explored by increasing the number of sub-options in each of the functional groups by ten fold.

[Google 2010]. By assessing recalculated characteristics and the performance of each option, a rapid down selection process could be readily implemented. Furthermore, if part of this down selection process occurs at a sub-option level, by making use of an appropriate subset of the current ship requirements, then this will significantly reduce the number of combined options that have to be considered using the library method. The possible combinations of remaining sub-options could then be used to produce a set of combined options. Finally, the set of combined options, that satisfy the complete set of constraints and requirements, could then be found.

The constraints and requirements that are used to remove unacceptable combined options can be used to ensure the options are 'balanced' (e.g. a constraint on weight vs. displacement could be used to remove Archimedially unbalanced designs). While, an iterative sizing method (such as [UCL 2002]) could be employed to re-balance the combined options, its drawbacks are worth considering. Burcher and Rydill [1994][5] highlight the large number of inter dependencies occurring in even a simple four-component weight breakdown. As a consequence, the re-balancing process may be highly sensitive to these inter dependencies when exploring a solution that departs from current practice. By using constraints to ensure the options are 'balanced', the re-balancing step can be avoided and effort can be dedicated to exploring alternative options.

Section 2.1.1 outlined the characteristics of the concept phase of the ship design process. As this approach is intended to be used in this phase, it is important to recall the particular needs of this phase. The fluid and exploratory nature of the concept phase of the ship design process means that new information is highly likely to arise. It should be easy to incorporate such information into the design knowledge repository used by the proposed Library Based approach. This then leads to a requirement for a mechanism, which allows the addition of new information. A Library Based approach is well suited to incorporating new information as it arises during the design process. Options or sub-options can simply be added to the library, to either broaden the library of add detail in specific areas.

Thus this section suggests that a Library Based ship concept design approach could provide a simple mechanism to rapidly explore the impact of a set of requirements upon whole ship options. The proposed method uses a search and combination approach to explore potential options. This method avoids some of the difficulties identified in design automation and optimisation methods that aim to develop a single "best" solution. Rather, it aims to facilitate a better exploration of potential solutions through the identification of both workable and unworkable options.

5.2.2 Comparison with Other Similar Methods

Of the seven approaches to the ship design methods presented in Chapter 3, the Library Base approach presented here is most similar to that of Concept Exploration Methods

[5] In their Chapter 11 describing the 'Character of iterations'.

(CEM) considered in Section 3.2.2. CEMs allow the designer to explore a wide variety of potential solutions generated via a parametric synthesis process. CEMs generate these solutions at a whole ship level, while the proposed Library Base approach does so by generating and combining sub-options. Additionally, the synthesis models used within existing CEMs have been limited to consideration of just one hullform style (with the notable exception of [Molland and Karayannis 1997] with two styles). The use of a Library Based model, as proposed, would provide a clear distinction between the task of generating options for the library and the subsequent exploration of these options. This task separation has the potential to free the designer from using just a single synthesis model and allowing options produced by a number of different synthesis models to be examined. There are also parallels between the simple search process employed in the proposed method and the mechanisms outlined in Section 4.2.1. Yoshikawa's General Design Theories (GDT and GDT-Real [Reich 1995]) are analogous to the proposed selection methods (but suffer from the practical limitation that they require ideal knowledge). C-K theory as proposed by Hatchuel and Weil [2003] incorporate the important iterative process of knowledge collection (an important issue foreseen by March [1984]). The proposed approach contains elements of both GDT and C-K theory: the rapid down selection made possible by the library is similar to the approach Yoshikawa proposes for using requirements to remove items from consideration [Reich 1995]; while C-K theory highlights the importance of developing design knowledge during the design process [Hatchuel and Weil 2003], which can easily be achieved in the proposed approach by expanding the library.

The proposed design approach employs a database to store design options. Heather [1993b] identifies concept exploration backed by databases as one important component of an integrated warship concept design system. Database supported design methods are identified by Nowacki [2009a] as being one of nine new traits and capabilities that he views as essential in modern ship design methodologies. He describes how the information and knowledge stored within a database can be used to 'initialise new design processes'. By making uses of a database system to store design information, the proposed approach is similar to the tools presented by Schiller et al. [2001] and Molland and Karayannis [1997]. Those tools both make use of databases to store design information (including potential options). However, both those tools require a synthesis step to be performed to develop complete ship options and this step requires a large number of designs to be developed. In both these approaches the synthesis step occurs after the designer has begun using the tool which will consequently increase the timescale required when using these approaches. Furthermore, both these methods would be difficult to apply in assessing a very large number of options with several distinct hullform styles (although the tool presented by Molland and Karayannis [1997] has been used successfully to compare monohulls and catamaran passenger ferries, it is not obvious how it could be readily extended to other ship types).

Moving beyond marine design, a number of other fields of design have made extensive use of libraries, databases or similar data collections to support design work. This includes materials engineering tools for the selection of materials, the recording of design information and specifying different manufacturing processes. Examples include [Birmingham and Wilcox 1993], who demonstrate how simple graphical representation can be used to gain significant insights into the utility of particular materials for a given design problem based upon libraries of materiel attributes. Methods to aid the designer in tackling material selection, when non-numerical attributes are important, have also been developed [Ashby et al. 2004]. Beyond engineering design, Library Based approaches form key tools for use within combinatorial chemistry—the technique of rapid synthesis (and automated testing) and the computer simulation of the behaviour of a large numbers of related molecules [Wilson 1997]. This technique has been applied to speed up the discovery of new pharmaceutical compounds and materials, such as catalysts. By employing automated tools to explore a wide design space the user gains information on promising combinations of options. These options could then be further assessed outside the Library Based approach using other design approaches and tools.

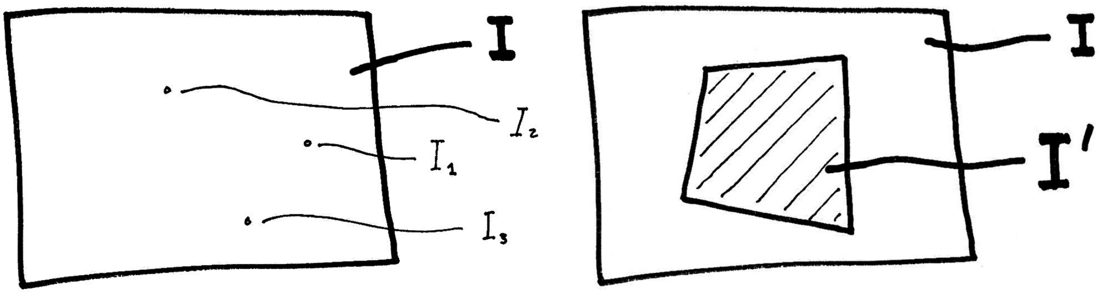
5.3 Assumptions Underlying A Library Based Approach

This section develops the approach underlying the library method from a simple definition, which is initially abstracted from a ship design problem. The underlying approach is discussed in six sub-sections. Section 5.3.1 begins by setting out a framework in which the a library of options, can be developed. Next, the high level approach adopted for prediction of the performance of whole ship options is described in Section 5.3.2. Sections 5.3.3, 5.3.4 and 5.3.5 then address the three interconnected issues as to how options are managed in the approach, namely: Decomposing Options; Removing Options; and Adding Options. Finally, Section 5.3.6 provides an illustrative example of how a Library Based approach could be used in the exploration of options for ship concept design.

5.3.1 On the Development of the Design Method

Initially, a continuous space $\mathbf{I}$ can be defined containing all possible potential design options $(I_1, I_2, I_3, \dots)$, as shown in Figure 5.4a. This space defines an infinite number of options. Any option from this set can be retrieved and its attributes examined, either directly or using a suitable prediction method. If the infinite design space $\mathbf{I}$ were bounded by some arbitrary limits (representing the limits of current knowledge regarding the design space) a finite space will be obtained which will be denoted by $\mathbf{I}'$, as shown in Figure 5.4b.

Ideally, a designer would obtain options directly from the bounded space $\mathbf{I}'$ (i.e. the space could be described in terms of simple functions and then a solution obtained by solving



(a) Infinite Space $\mathbf{I}$

(b) Bounded Space $\mathbf{I}'$

Figure 5.4: A comparison of an Infinite Space and a Bounded Space

these functions, using the initial requirements as an input[6]). However, some characteristics of marine vehicles give rise to a discontinuous design space, which means it is inappropriate to evaluate potential options through simple continuous functions. A possible compromise is to represent the space through a number of discreet options. Unfortunately, as the space $\mathbf{I}'$ is continuous it has to be described by an infinite number of options $(I_1, I_2, I_3, \dots)$. However, if the options are restricted to a fixed number m, distributed randomly across the space, then a discrete design space $\mathbf{I}^\star$ is obtained to describe the set of options being considered, as shown in Figure 5.5.

This discreet set of options can be compared to a set of requirements to find the options that fulfil all necessary requirements and constraints, with the unsatisfactory options being discarded. This is similar to the approach adopted in previous concept exploration models, as has been discussed in Section 3.2.2. However, in order to reasonably represent the solution space, the options must be distributed throughout the space with an appropriate level of granularity and this then leads to a large number of options required to be considered.

One possible approach to this problem is to consider a mapping which could decompose a single option into a number of sub-options. The sub-options can then be combined to produce a far larger set of combined options. However, this approach depends upon the decomposition process the designer employs to obtain the sub-options. Considering a single option I from within the set $\mathbf{I}^\star$, then by applying some mapping to decompose the option, a number of sub-options could be produced. The case of a mapping which would decompose the option I into three sub-options (I_A, I_B, I_C) gives:

$$I \mapsto I_A, I_B, I_C$$

[6]Notwithstanding the issue of non-compliance in the requirements as discussed in Section 2.3.4.

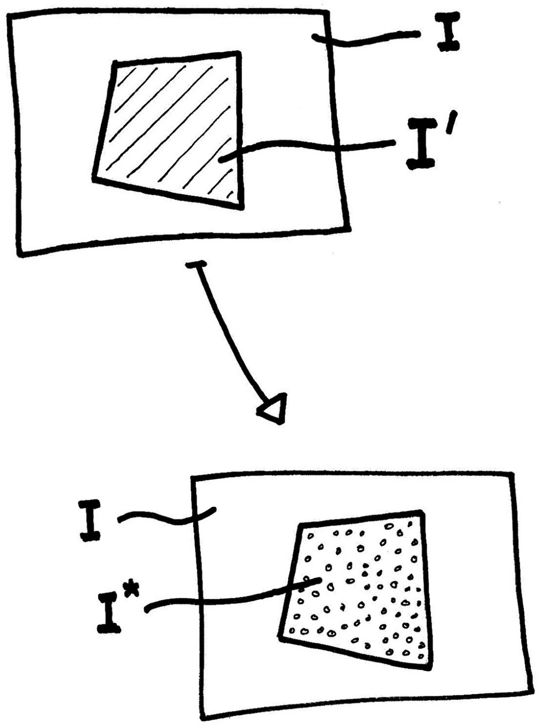


Figure 5.5: Bounded Space Approximated via a Limited Set of Solutions, $\mathbf{I}^\star = \{I_1, I_2, I_3, \ldots, I_{m-1}, I_m\}$

This mapping is illustrated in Figure 5.6. Before discussing the practicalities of constructing a mapping able to decompose an option, it is considered appropriate to firstly explore performance prediction for options.

5.3.2 Performance Prediction for Options

The performance and characteristics of any option can be thought of as a set of attributes $(a_1, a_2, a_3, \ldots)$ and these are governed by relationships linking them to other attributes of the option. For example, if the option under consideration were a monohull ship then the waterline length can be derived from other attributes, as shown by the following well known relationship:

$$L = \frac{\nabla}{C_B B T} = f(\nabla, C_B, B, T)$$

Similar methods can be applied to predict or calculate other attributes of interest (e.g. either the option's achieved performance, features or gross ship characteristics [Andrews 1984]). Some ship attributes are amenable to simple analytical relationships (i.e. small angle stability). Other attributes must be evaluated through more complex methods (i.e. seakeeping analysis—see [Lloyd 1989]) and such methods are, typically, difficult to ap-

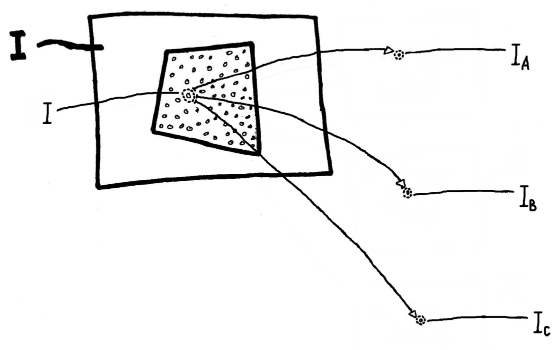


Figure 5.6: Decomposing an Option I into Three Sub-Options (I_A, I_B, I_C)

ply in the early stages of the design process, since they require detailed information not normally generated in the concept phase. Furthermore, it is hard to develop analytical prediction methods that are robust, accurate and generalised with the limited design definition available at concept. The difficulty in predicting these more complex attributes has led to the generation of a range of empirical and semi-empirical performance prediction methods for concept work. Recent research on artificial intelligence methods considered in Section 3.2.5[7] explores the development of advanced prediction algorithms, based upon the information likely to be currently available to a concept designer, which could provide rapid prediction of some ship attributes. A number of these approaches, other machine learning methods and even regression analysis could be used to develop prediction methods that may also be easy to update.

In general, prediction methods can be thought of as determining the value of an attribute based upon other attributes. If these attributes are collected together in a vector ($\mathbf{x}$), then any attribute (a) can be found via some function acting upon this vector:

$$a = f(\mathbf{x})$$

However, given the complexity apparent within any ship, the vector $\mathbf{x}$ will be very large. Additionally, for many attributes the vector $\mathbf{x}$ will contain redundant information, such as other attributes that are unconnected or only weakly connected to the attribute under consideration. Current design methods draw out these important relationships. For example, the UCL MSc design procedure provides a set of equations linking the hull dimensions, mass and volume for a monohull warship [UCL 2002, 2004]. By examining these equations, relevant relationships are revealed.

Figure 5.7 collects together the key variables in the sizing equations taken from [UCL 2002, 2004]. For each key variable listed along the top of the figure, the variables upon which it directly depends are indicated in the column below (using a • symbol). For

[7]Specifically [Ray 1998], [Cocodia 2005] and [Maroju et al. 2006].

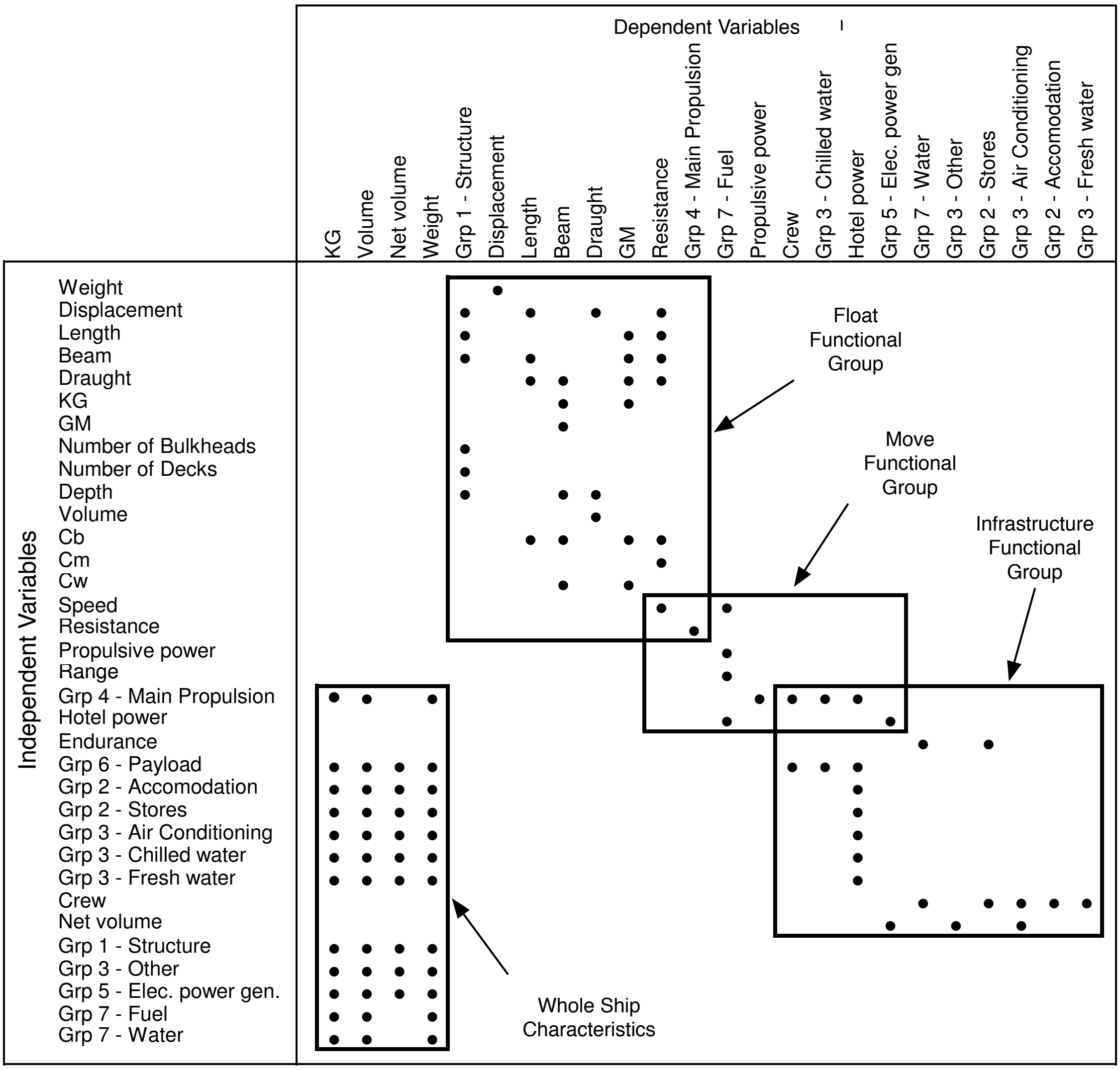


Figure 5.7: Clustered Relationships Between the Key Variable based upon data from UCL Ship Design Process [UCL 2002, 2004]

example, the UCL ship sizing procedure defines draught (the dependent variable) through a relationship between displacement, volume and depth (the independent variables). The columns in Figure 5.7 have been arranged to collect variables in clusters of closely related attributes. These clusters can be seen to match those used when decomposing a ship into functional groups (other authors have previously proposed applying decomposition in ship design without proposing a specific link back to functional groups [Tan and Sen 2001]). Additionally, a fourth cluster emerges describing whole ship characteristics, which are similar to Gross Ship Characteristics (GSC) defined in [Andrews 1984]. Current design methods, such as [UCL 2002], iterate the whole ship attributes in this cluster until a balanced solution emerges. This tabular summary of related attributes is somewhat like the Design Structure Matrix technique discussed in Section 3.2.4, although the primarily concern in using the Design Structure Matrix technique is more efficient resourcing of the steps in the design process.

A number of the attributes that are more difficult to predict, such as resistance, can be seen to lie within a single cluster. If other complex prediction methods are considered some of the attributes can be similarly restricted to a single cluster (i.e. seakeeping and large angle stability are predominantly dependent upon the hullform shape, displacement and the position of the vertical centre of gravity and hence are associated with the Float functional grouping). For those attributes that are difficult to predict, it is advantageous to pre-calculate and store their values within the library. In comparison, overall vessel attributes are comparatively easy to evaluate (i.e. mass and volume are simple summations of scalar values) and so they can be rapidly determined from the attributes of the sub-options. This can be done by using the UCL weight and space algorithms [UCL 2002] to determine attributes of specific groups in each sub-option, then totalling the sub-option's attributes to give the required combined option attribute.

It is appreciated that there are other attributes that will be far more difficult to predict. In such cases, an appropriate, sufficiently fast calculating, prediction method will need to be applied in order to determine the attributes of interest. For example, to find the ship's seakeeping response, the prediction method should make use of both the hullform's hydrodynamic attributes (an attribute of the Float function) and whole ship attributes, such as the vertical location of the centre of gravity and the radii of gyration. The ship's response could be determined by several methods, including: directly from pre-calculated hullform hydrodynamic attributes (stored in the library) and the whole ship attributes; by interpolating between values of ship response determined for different values of whole ship attributes; or, from simple equations or empirical relationships, if available (e.g. Lloyd 1989, 1992). However, some whole ship attributes, such as vertical centre of gravity, are particularly dependent on the ship's configuration. It would seem that the majority of ship attributes that are difficult to predict appear to be driven by layout. For example, survivability is a strong driving factor in warship concept design [Manley 2004]. Current methods used to assess survivability require a highly detailed design definition to be produced [Schofield 2007]. Consequently, the large number of interrelated variables under consideration complicate the application of this decomposition method in such instances. However, some elements of the survivability calculation (i.e. the effect of blast propagation) could be performed at the level of a specific functional group. This would still provide relevant information for a designer in the concept phase.

It should be noted that the Library Based approach is flexible with regards to the sub-option data which is precalculated and stored in the library. The designer is free to utilise data generated using any tool (or collection of tools) to populated the library. It is envisaged that a designer would employ design tools already used within their design organisation to develop library data. When considering a wide range of design styles a number of different design or analysis tools may need to be employed. This could lead to a requirement to alter existing design tools so they are able to develop a range of design parametrically [Cooper et al. 2007].

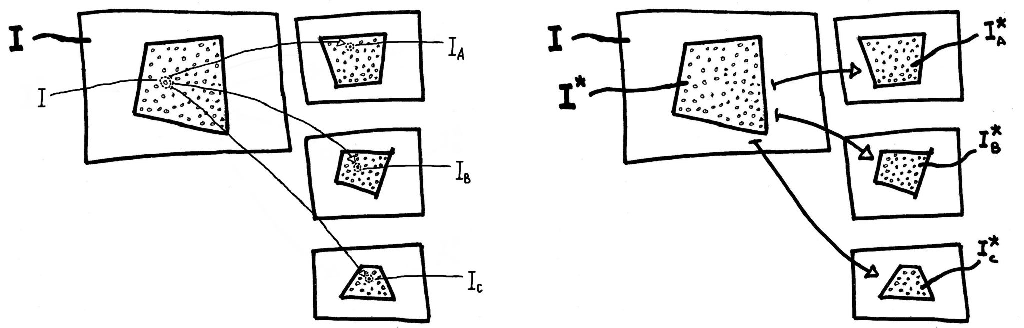
5.3.3 Decomposing Options

The concept of decomposing options via a mapping ($I \mapsto I_A, I_B, I_C$) was proposed in Section 5.3.1. It is possible to generalise this mapping to the elements of a set $\mathbf{I}^\star$, to give:

$$\mathbf{I}^\star \mapsto \mathbf{I}^\star_\mathbf{A}, \mathbf{I}^\star_\mathbf{B}, \mathbf{I}^\star_\mathbf{C}$$

This mapping is depicted graphically in Figure 5.8b. This mapping can be inverted and a collection of higher level options be obtained from a number of sets containing sub-options:

$$\mathbf{I}^\star_\mathbf{A}, \mathbf{I}^\star_\mathbf{B}, \mathbf{I}^\star_\mathbf{C} \mapsto \mathbf{I}^\star$$



(a) An Option (I) Decomposed to Three Sub-Options (I_A, I_B, I_C)

(b) A Set ($\mathbf{I}^\star$) Decomposed to Three Sub-Sets ($\mathbf{I}^\star_\mathbf{A}, \mathbf{I}^\star_\mathbf{B}, \mathbf{I}^\star_\mathbf{C}$)

Figure 5.8: Decomposition of an Option into Sub-Options and a Set into Sub-Sets

The previous section introduced the idea that clusters of connected variables could be grouped together to allow some ship characteristics or performance to be defined at a functional group level. Therefore, by applying a decomposition approach based upon functional groups, an overall ship option could be separated into a number of functional group sub-options, albeit with some connections between the groups for specific super functional group ship characteristics and performances.

Up to this point the discussion has been largely framed in terms of abstract options. At this stage it is useful to consider a ship based example. If initially a ship option S_S is considered then this option could be compared to a set of current requirements to determine if it is an acceptable solution for this requirement set. Requirements used to assess the ship option may include overall ship performance attributes, such as maximum range at a specified speed. Returning to the ship option and applying the reasoning presented earlier, S_S can be decomposed into four sub-options S_F, S_M , S_O and S_I (representing the Float, Move, Operations (or Fight) and Infrastructure functions respectively). Then we have $S_S \mapsto S_F, S_M, S_O, S_I$ and the inverse relationship $S_F, S_M, S_O, S_I \mapsto S_S$[8].

The designer wishing to develop a ship to meet a new collection of "customer" needs could define a new sub-option S_O that describes the Operations related systems required in the new ship. Alternatively, this could be expressed via an additional set of requirements R_O that includes the constraints imposed by the ship's Operational items (i.e. ensuring there is sufficient available space or crew to support these items)[9]. In this case, feasible whole ship options, excluding Operations related whole ship systems demands, can be found by combining three sub-options S_F , S_M and S_I via a mapping such as $S_F, S_M, S_I \mapsto S_{(S-O)}$ where $S_{(S-O)}$ indicates the combined ship option excluding the demands of the Operational items. These combined options ($S_{(S-O)}$) can then be compared against the set of requirements R_O to find those that meet the Operations related requirements.

Using an equivalent notation to the start of this section, it is possible to define sets containing the ship options excluding the demands of operational items $\mathbf{S_{(S-O)}}$ and the three sets of functional sub-options $\mathbf{S_F}$, $\mathbf{S_M}$, $\mathbf{S_I}$. As a first approximation, the number of possible options within the set $\mathbf{S_{(S-O)}}$ is determined by the possible combination of functional sub-options from the sets $\mathbf{S_F}$, $\mathbf{S_M}$, $\mathbf{S_I}$. This is seen as a useful approach as it separated the essentially user 'needs' from the whole ship (Float, Move and Infrastructure) driven issues.

5.3.4 Removing Options

If the number of options is dependent upon the possible combination of sub-options, removing any functional group options from consideration should rapidly reduce the number of ship options in the whole ship set $\mathbf{S_S}$. Two methods exist for removing sub-options from consideration. First, sub-options can be removed by comparing their characteristics against external requirements (e.g. a Float sub-option (i.e. hullform) with insufficient upper deck length to accommodate the Operational items). Alternatively, sub-options could be removed from consideration by detecting incompatibilities across the sets of sub-options

[8] It is important to note that these relationships do not state that the ship option is the 'sum' of four component parts. Rather, given a set of component parts, the mapping can be used to produce a ship option. Furthermore, this ship option may possess a number of emergent properties (some categorised as transversals [MoD 2005b]) that are beyond those that may be expected from examining the functional components alone—i.e. 'the whole is more than the sum of the parts'. Andrews presents this separation in Figure 5.4 of [Andrews 2003a] through the distinction between Warship Systems (encompassing systems described via the Float, Move, Infrastructure and Fight functional breakdown) and Project Issues (representing the Integrated Logistics Support, Management and Design Integration issues that occur across the project). Section 5.3.2 has highlighted how some of Andrews Project Issues could be partially addressed by a Library Based design approach.

[9] Note that the set of 'operational' requirements R_O is in addition to the other requirements that have been developed to represent the customer's other needs (e.g. maximum speed, endurance, etc.).

(e.g. a Float sub-option with insufficient available volume to accommodate a specific Move sub-options).

Incompatibilities could be examined for both an individual option and for sets of options. For example, if the power required by a Float sub-option is more than the power supplied by a Move sub-option, these two options are incompatible (i.e. if a Float sub-option requires 30MW to attain the required top speed but a Move sub-option only supplies 20MW, then a combined option containing these two sub-options would be infeasible). Alternatively, the maximum power produced by a set of Move sub-options can be found and used to remove from consideration members of the set of Float sub-options that require a higher power to achieve the desired operating speed (i.e. if the largest maximum supplied power of a set of Move sub-options is 20MW then any Float sub-option requiring a greater power at the required top speed would be infeasible and can be removed).

5.3.5 New Options

For the proposed design method it should be possible to add new options to the original finite set of options. New ship options ($S_{\bar{S}}$, where the bar indicates a new option) could be added directly at the top level (as part of the set $\mathbf{S_S}$). Also, a new option could be introduced at the functional level (e.g. $S_{\bar{F}}$), by combining this Float functional level option with existing Move and Infrastructure functional level options will result in a new ship (excluding Operational items) option ($S_{\overline{(S-O)}}$).

$$S_{\bar{F}}, S_M, S_I \mapsto S_{\overline{(S-O)}}$$

Note that at this stage the performance, and indeed the feasibility, of this new option is unknown. Therefore, the characteristics and performance of the new option must be assessed and compared against the requirements of interest to the designer to determine if it presents a viable option. This can take place at both the functional group level and the ship level. The earlier section on performance prediction for options suggested that a number of the top level characteristics are easy to assess. For example, performance characteristics, such as large angle stability, could be assessed using a GZ curve for the complete ship. This GZ curve can be determined from a SZ curve for the hullform (an attribute of the Float function) and the ship's SG value (from the ship's vertical centre of gravity; an attribute of the combined option[10]) using a standard method, for an example see [Rawson and Tupper 2001]. Furthermore, a balanced design could be assessed at this point by ensuring satisfactory relationships between the required and available values for characteristics, such as mass, volume and crew numbers.

[10]Although, a designer could also decide that it is appropriate to use a default value for the vessel's vertical centre of gravity (e.g. a fixed proportion of the main hull depth derived from type ship data). This would allow the GZ curve to be developed using attributes of just the Float function.

Not all characteristics will be amenable to a simple assessment, thus other approaches may have to be used. The range of established analysis tools or methods able to address these more complex issues could be employed. Such tools and methods will inevitably result in increases in calculation time. Thus this approach is likely to be unattractive when evaluating all potential options. However, each option will belong to a larger set of similar options. As a result, some characteristics can be determined or inferred from these other options. For some options in the library, empirical data may be available. Alternatively, the time-consuming application of analysis tools can be conducted 'off line' to the selection of the options from the library, building a collection of firm data. From this collection of data approximate prediction methods could then be developed. These would then enable a rapid assessment of attributes, although any assessment is likely to be approximate. In terms of ship and functional group options, the database of available information on ship options or functional sub-options could be used to rapidly predict the performance of a new ship option. The advantage of a store of this type of information is that, as new data are generated, they can be easily added into the library, leading to improvements in the prediction methods over time.

An example of the benefits of this approach arises when considering performance prediction for different hullform styles. For some hullform styles, data will initially be sparse and any prediction methods developed only approximate, as is the case with current concept design practice. However, if some form of modelling produced more performance information then the performance prediction tool could be readily updated. As the library of design options expands, performance prediction methods will be enhanced so improving the overall design process. The ability to simply incorporate new information into the prediction techniques can be seen as analogous to March's PDI (as discussed in Section 4.3.1) as a cyclical process of abduction, deduction and induction (i.e. proposing a new design, finding its 'real' performance, then using this information to improve the available prediction tools). While the Library Based approach implies that the overall design process can be improved, by using a set of solutions, it differs from March's description (which focused upon a single design [March 1984]) since the approach still externalises information in a way that is clear to all design participants. This is achieved by incorporating designs into the library, which will enable a gradual improvement to the ship design process through the acquisition of knowledge in the library.

5.3.6 Illustrative Example of the Options Exploration Process

This section presents an illustrative example, at Figure 5.9, as to how the elements described in the previous sections are combined into a process able to explore a library of sub-options to meet a set of requirements. At the left of Figure 5.9 are the sets for the sub-options containing the three functional groups ($\mathbf{S_F}, \mathbf{S_M}, \mathbf{S_I}$) stored within the library (marked as Figure 5.9a). These sets of sub-options are then assessed against appropriate

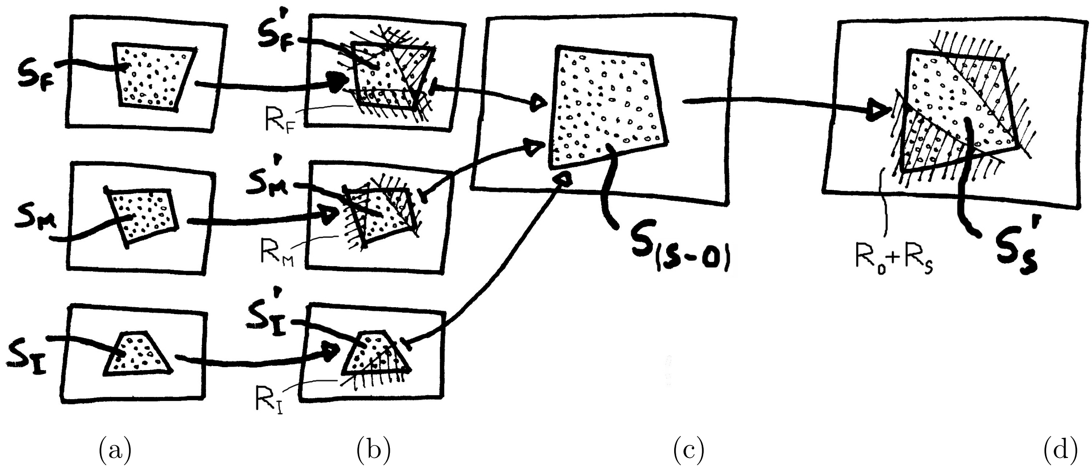


Figure 5.9: An Illustration of the Option Exploration Process

subsets of the requirements (R_F for the Float options, R_M for the Move options and R_I for the Infrastructure options). Those that fail are then removed from consideration. The subsets of the requirements will differ between the functional groups, for example the Float sub-options that are to be removed from consideration could be initially down-selected on the basis of an overall length requirement, which would remove the inappropriate hullforms (e.g. those too long to meet docking constraints or those too short to accommodate the upper deck operational and other items (e.g. boats, deck equipment)). This would leave three sets of acceptable sub-options $\mathbf{S'_F}, \mathbf{S'_M}, \mathbf{S'_I}$ (Figure 5.9b). By employing the mapping discussed earlier, these three sets of sub-options could then be combined into a new set of combined ship options that exclude the demands of the operational items $\mathbf{S_{(S-O)}}$ (Figure 5.9c). Again the appropriate requirements could be used to remove further unacceptable options. This includes both those requirements originating from the demands of the Operations functional group R_O (e.g. those without enough available space to accommodate the operational, infrastructure and machinery items) and those ship requirements R_S that encompass other customer needs and span several functional groups (e.g. an endurance requirement for a particular speed). Assessing these requirements could be achieved through the following sequential process: applying ship requirements (R_S) to the combined options to remove unacceptable options, leaving acceptable combined (Float, Move, Infrastructure) options minus operational items' $\mathbf{S'_{(S-O)}}$; then applying the remaining operational demands (R_O) to obtain viable whole ship options that can accommodate the payload $\mathbf{S'_S}$. While this could be performed as a two sequential steps, each step is an equivalent down selection process where the only difference is the source of the requirements.

When assessing some of these operational and whole ship requirements, performance prediction methods may need to be employed. In such cases, an appropriate method can be used to account for major interactions between sub-options. For example, given a requirement to assess the endurance of a combined option at a given speed, a number of performance prediction methods could be employed: a simple method may compare the resistance of (and hence required power for) the Float sub-option against the maximum power the Move sub-option could deliver over the time required for the transit[11]; a more complex method may follow a similar logic but attempt to better address important interrelations, such as the losses cause by hull–propulsor interaction, given other information stored within the library. Additionally, an appropriate correction (such as the seakeeping example given in Section 5.3.2) may need to be applied, in order to successfully complete the down selection. The requirements that require complex performance prediction methods will be harder to evaluate than those requiring methods using simple performance predictions, such as an algorithm or traditional 'rules of thumb'. Therefore, it is advantageous to perform the simpler and quicker down selection methods first, avoiding applying computationally expensive methods unnecessarily. However, this will also result in the final set of acceptable combined whole ship options $\mathbf{S}'_{\mathbf{S}}$ having sufficient allowances to support the operational items (Figure 5.9d). This collection of options would then be presented by the tool to the designer.

5.4 The Library Based Approach in a Ship Design Organisation

It is useful to consider how the Library Based approach, outlined in Section 5.2 and detailed in Section 5.3, would be employed by a designer working in a design organisation. It is envisaged that the tool would be employed at the outset of the design process, as both an aid to support discussions with the customer and also to provide assurance to the designer that their initial decisions on style are correct. In this context an experienced designer would employ the tool to rapidly examine the customer's requirements (either with or without the customer present). As input the tool requires both a definition of the current requirements and of the payload items, which the designer would provide. Using these inputs the tool would be run, with the sub-options in the library being down selected against both the requirement and payload input by the designer, the remaining sub-options would then be combined and down selected until all constraints have been assessed. Finally, outputs detailing the combined options able to support the payload and meet the performance requirement would be returned by the tool. This information would then be presented to the designer in a number of different formats to convey either,

[11] Noting that a given endurance requirement (in terms of range at a specific speed) can be converted into the time a vessel must operate in this condition. Given that the Move sub-option contains a description of both the installed machinery and fuel capacity, this information can be determined across the vessel's operating range.

information on the remaining option's styles or gross characteristics, or, information on the performance and characteristics of these options.

To use the tool as described in the preceding paragraph, it is necessary to first generate a suitable library of options containing the appropriate design information. It is envisaged that a design organisation would generate a library of sub-options before the designer begins using the tool. While this precalculation stage could be conducted as a one off activity, there may be considerable merit in an organisation growing the library over time, as concepts are explored using other tools. It is recognised that each organisation is likely to generate a library (or libraries) tailored to the concepts they expect to explore, however it is important that the library remains sufficiently broad so as to cover subsequent unexpected studies[12]. Furthermore, the tools, methods and procedures, which any design organisation would employ to generate the options or sub-options within their library, are likely to be distinct. An additional benefit of adopting the Library Based approach is that it also provides the design organisation with a single location where they can maintain information; adding details of new sub-options as alternative technologies or concepts are developed or removing those sub-options that are no longer acceptable due to externally imposed constraints (i.e. those that fail to meet the applicable safety standards).

The Library Based approach employs requirements to down select sub-options and combined options. The designer is responsible for specifying these requirements. However, when considering some requirements used to ensure balance between characteristics, such as weight and buoyancy, there are two differing alternatives a designer could adopt:

- The designer could apply requirements that reflect the classical balance naval architects employ (e.g. a solution balanced using Archimedes' principle: weight = buoyancy) to down select combined options;
- The designer could identify and remove the combined options which are unacceptable (e.g. weight > buoyancy). The remaining combined options are therefore either balanced (e.g. weight = buoyancy) or loosely-balanced (e.g. weight < buoyancy).

Adopting the second of these alternatives, where loosely-balanced combined options are retained, has significant consequences. By not imposing the strict requirements related to a balanced solution a large number of options are kept open until later in the design process. Figure 5.10 shows how retaining loosely balanced options could increase the number of options being considered.

By considering these loosely balanced options the Library Based approach may be able to identify combined options that have previously been excluded from consideration. For

[12]For example, an organisation such as the UK Ministry of Defence could construct libraries for the different types of vessels: Offshore Patrol Vessels and small craft; Frigates and Destroyers; Amphibious Assault Ship and Aircraft Carriers; and Naval Auxiliaries. Alternatively, a single library containing sub-options representing these discrete options and a range of intermediate solutions could be developed for exploring unconventional set of requirements.

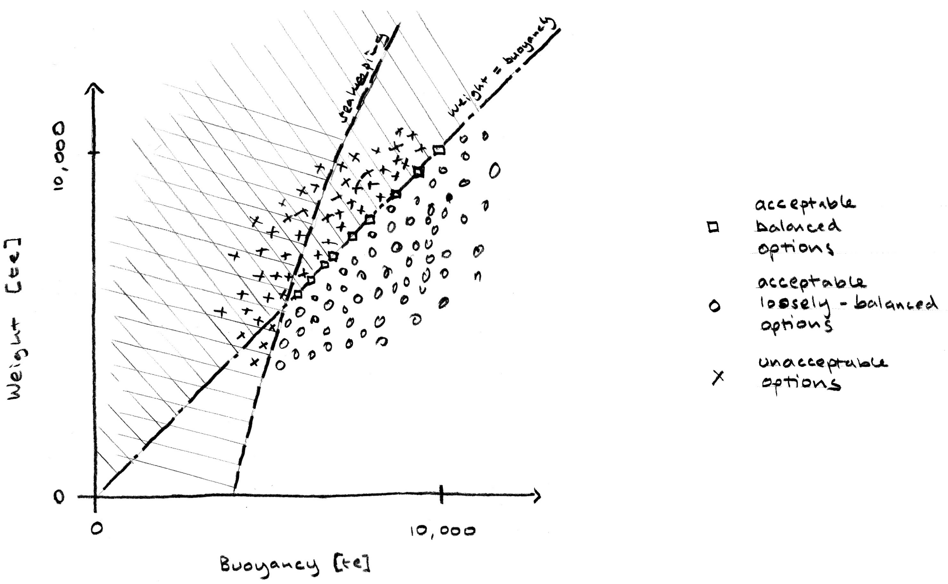


Figure 5.10: Illustrative Plot of a Theoretical Set of Outputs from the Library Based Approach showing Balanced, Loosely Balanced and Unacceptable Options in response to the Application of Two Requirements

example, for a monohull a desire to minimise ship motions could be satisfied via an enlarged hullform (to improve seakeeping performance). If only balanced designs were examined then the balanced options emerging from the combination or down selection process may feature growth in weight and cost across the different functional groups leading to expensive combined options. However, if loosely-balanced options are retained then the Library Based approach offers the potential to identify combined options that satisfy the requirements but are not classically balanced (e.g. an enlarged Float sub-option where the hullform's dimensions are driven by required seakeeping performance, c.f. sufficient buoyancy to support the weight of the different functional groups). These concepts may then be inspected and modified to achieve balance (i.e. in the case of an an enlarged Float sub-option, through augmenting the combined option by simply adding ballast or some other less obvious, designer led approach).

The Library Based approach also has the potential to enable the designer to assess ship concept design options with different styles. This is considered in more detail in Chapter 8 (Section 8.3.2) after the Library Based approach has been developed through a range of example in the next two chapters.

5.5 Definitions of Key Terms

A number of key terms describing the Library Based approach have been defined in this chapter. For the convenience of the reader these are collated in Table 5.2.

Table 5.2: Definitions of Key Terms used in Describing the Library Based Approach

Term	Definition	Example
Option	A specific discrete design point.	A Ship option, representing a single point design for a ship.
Sub-Option	A specific discrete design point that is a sub-function of the ship.	A Move sub-option, representing a single point design for a sub-function of the whole ship (i.e. a set of machinery and a fuel capacity).
Combined Option	A new option created from a number of sub-options.	A combined Float–Move–Infrastructure option, representing an option synthesised by combining Float, Move and Infrastructure sub-options.
Characteristic	One of the different properties an option possesses.	An overall length characteristic belonging to a Float sub-option; A weight characteristic belonging to a Move option.
Value	The numerical amount attributed to a particular characteristic.	An overall length characteristic would have a value such as 100m.
Performance Prediction Method	Method employed to determine the value of a characteristic.	A performance prediction method that estimated a value of a Move sub-option's cost characteristics based upon the weight and installed power (i.e. £xM).
Requirement	A constraint on a characteristic (or characteristics) employed in the down selection of acceptable options.	A requirement that the overall length should be below 300m; A requirement that the installed power should be greater that the power required at maximum speed (derived from a particular hullform and displacement).

5.6 Hypothesis

This chapter has proposed a Library Based approach to preliminary ship design. It is suggested that this approach could provide a mechanism for facilitating exploration of significantly different options at the outset of the design process. Furthermore, such a Library Based tool may be able to bridge the conceptual gap between the initial requirement and an identification of promising vessel styles. However, to resolve these uncertainties a key question has to be addressed:

> *Does a tool that employs the Library Based design approach present a viable mechanism for rapidly exploring options with different styles early in the design process?*

The viability of the approach is dependent upon its ability to conduct the type of down selection and combination operations described in this chapter. Furthermore, these operations should be performed in an amount of time that would allow the approach to be applied in the early stages of the ship design process[13]. Finally, the approach must demonstrate that it can also address options with a range of differing styles. The approach's overall viability should be demonstrated through its application to a representative design case.

Chapters 6 and 7 consider the above question via the development of two different design tools that adopt the Library Based design approach. Chapter 6 presents an initial exploratory implementation of the Library Based approach which explores the key issues related to developing options from a design. Chapter 7 presents an improved implementation that more comprehensively fulfils the intent presented in Sections 5.2 and 5.3 by considering the specific design style issue of hullform type.

[13]Table 3.2 has illustrated that it is difficult to identify a single comparable target time by examining the operation of current tools and approaches. However, a maximum target duration of 10 minute would match that reported by [Eames and Drummond 1977] in their work on Concept Exploration approaches.

Furthermore, wider work from the field of applied psychology highlights the importance of the 'human action cycle' to decision making, specifically the value in providing information to the decision maker as soon as possible [Norman 2002]. Norman identifies the benefits that are achieved if the duration of response are minimised during general human–tool interactions.

6 An Exploratory Implementation of the Approach

The previous chapter outlined a Library Based ship concept design approach as a potential mechanism for rapidly exploring options during the early stages of ship concept design. This chapter presents a brief description of how a simple Library Based ship concept design tool can work. This tool—termed the 'exploratory implementation'—encapsulates a subset of the Library Based approaches features, as presented in Chapter 5. The tool was developed to explore the elements of the approach which relate to the decomposition, down selection and combination of options. Firstly, Sections 6.1 and 6.2 describe more fully both the aims of the exploratory implementation together with its key features and technical details. Section 6.3 details the process used to generate the library of design sub-options. Next, Section 6.4 describes how a set of requirements can be used to develop a set of resulting options. Sections 6.5 and 6.6 summarise the results obtained from using two different sets of requirements to interrogate the library. These two sets of requirements have been obtained from two designs: a currently in-service naval ship and a concept design generated by UCL students. Discussion and conclusions on this exploratory implementation are finally presented in Section 6.7 and 6.8.

6.1 Aims of the Exploratory Implementation

The principal aim of developing the exploratory implementation is to demonstrate the validity of combining sub-options to form whole ship options. Additionally, it was also intended to demonstrate down-selection as a mechanism for the rapid exploration of the design solution space. As a consequence, the exploratory implementation is a 'breadboard' solution that demonstrates the feasibility of a Library Based approach for these two aspects. The exploratory implementation was not intended to examine all issues proposed in Chapter 5. The most notable exception is the lack of any feedback mechanism allowing progressive improvement of the knowledge of the solution space (March's domain theory [March 1984]). Consequently, this implementation does not support a PDI process following March's [1984] explanation as outlined in Section 4.3.1. Furthermore, a decision was also made to constrain the ship hull types (styles) this demonstration explores. Thus in this case, only monohull naval ships with simple direct drive propulsion systems have been investigated.

6.2 Overview of the Exploratory Implementation

As illustrated in Section 5.3.6 the options exploration process that occurs within a Library Based tool can be represented by Figure 6.1. Beginning with a library of sub-options a number of consecutive down-selection and combination steps can be used to generate a set of combined options which meet a set of requirements specified by the designer.

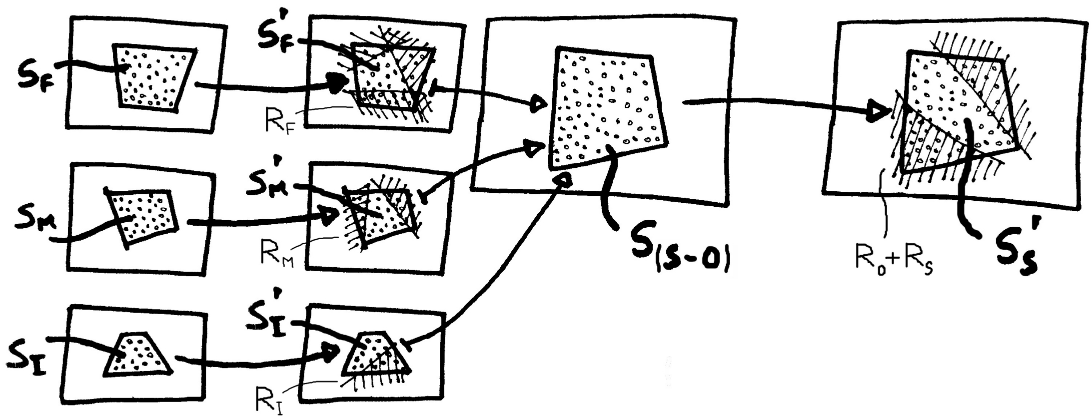


Figure 6.1: An Illustration of the Option Exploration Process (Repeated from Figure 5.9)

The exploratory implementation divides the ships into sub-options using three functional groups: Float; Move; and Infrastructure. Applying a functional group breakdown allows the designer to consider the options as distinct items with clearly identified interconnections. The requirements used in both down-selection steps are representative of the key requirements and constraints likely to act upon the design. Operational requirements are also used to identify options unable to meet the demands of the payload (e.g. payload weight, payload volume and payload crew demand). Initially, these requirements can be used to examine options at a functional group level with unacceptable options being discarded through a down-selection process. The remaining acceptable options were then combined to form whole ship options. These are then checked to ensure they meet all necessary requirements. The generic nature of these requirements should mean that the designer's bias and prejudices do not strongly influence the design process.

The key steps which occur when using the exploratory implementation are given below:

1. Create Float, Move and Infrastructure functional group sub-options;
2. Down selection of functional group sub-options using criteria derived from requirements specified by the designer;
3. Combine acceptable Float and Move sub-options to create combined Float-Move options;

4. Down select combined Float-Move options using criteria derived from requirements specified by the designer;

5. Combine the remaining combined Float-Move options with Infrastructure sub-options to form combined Float–Move–Infrastructure options;

6. Down select combined Float–Move–Infrastructure options to give final whole ship options.

The flow of information between these steps it shown in Figure 6.2.

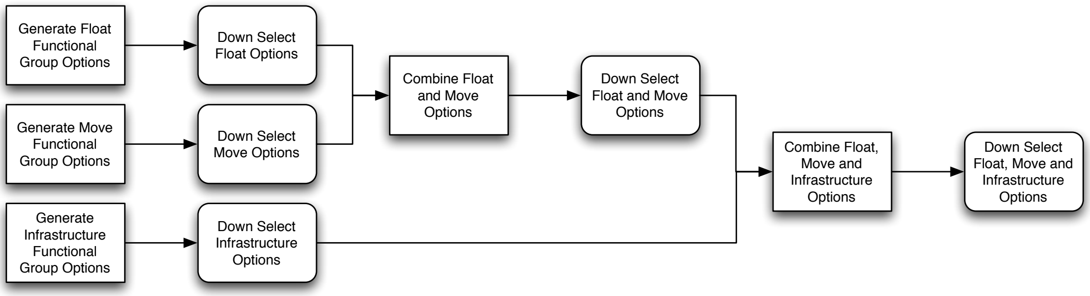


Figure 6.2: Flow of Information Between the Steps in the Exploratory Implementation of the Library Based Design Approach

6.2.1 Technical Details of the Exploratory Implementation

The exploratory implementation was developed using Microsoft Excel in combination with Microsoft Visual Basic. The implementation consisted of a main spreadsheet—which performed key data management tasks—and several additional spreadsheets—which performed performance prediction and sizing calculations. Figure 6.3 presents a diagrammatic representation of the flow of data both within and between the Excel spreadsheets. The rectangles bounded by dashed lines represent individual spreadsheets while the rectangles bounded by continuous lines represent the sheets within each spreadsheet.

The process shown in Figure 6.3 contains the following key steps:

1. Initially the main spreadsheet is populated with input data describing a number of sub-options (Figure 6.3, step 1);

2. This input data is passed to the separate spreadsheets in which the performance and characteristics are determined (including weight, volume and cost) for the different functional group sub-options (Figure 6.3, step 2);

3. The resulting output was then returned to the main spreadsheet (Figure 6.3, step 3);

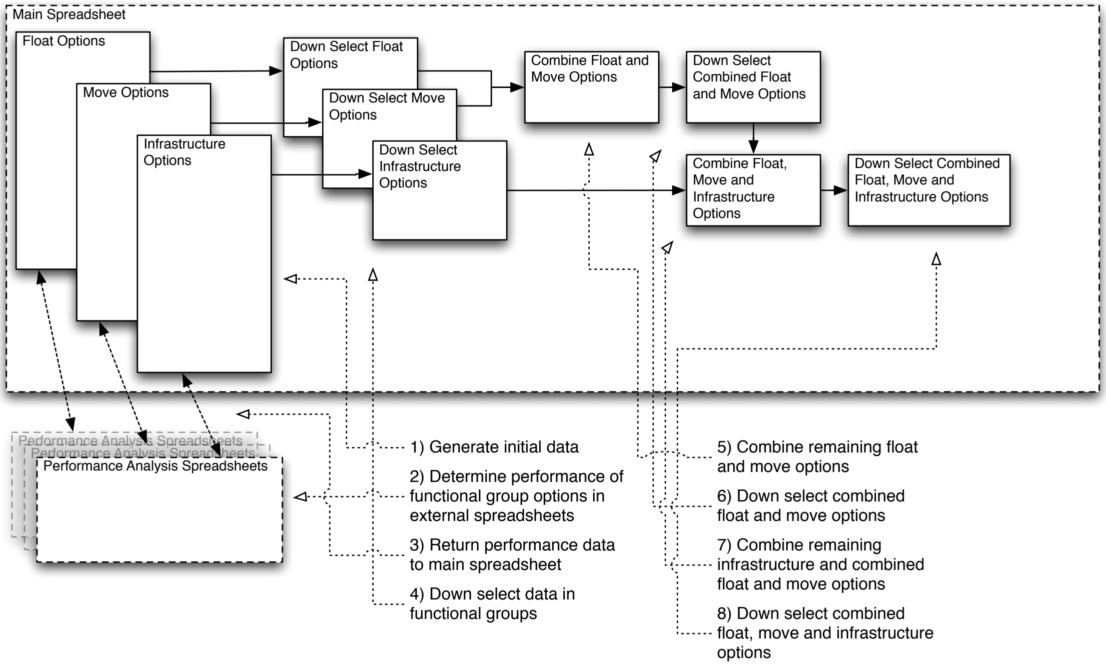


Figure 6.3: Flow of Data within the Excel Spreadsheet for the the Exploratory Implementation of the Library Based Design Approach

4. The sub-options for the three functional groups could now be assessed against a number of criteria based upon requirements input by the user. This process occurred on the three down selection sheets within the main spreadsheet (Figure 6.3, step 4);

5. After reducing the number of potential sub-options, the remaining functional group sub-options could be combined, this task was performed in four steps: Combining Float sub-options and Move sub-options; Down-selecting combined Float–Move options; Combining Float–Move options and Infrastructure sub-options; and Down-selecting combined Float–Move–Infrastructure options. First, the Float and Move sub-options are combined by creating a new row representing each combination of the Float and Move sub-options on a sheet within the main spreadsheet (Figure 6.3, step 5);

6. After this combination process, other characteristics can be evaluated for each combined option, such as the maximum speed and the maximum range at different speeds (give the fixed fuel load specified in the move sub-options). The resulting combined Float–Move options can then be assessed against further requirements enabling an additional down selection (Figure 6.3, step 6);

7. Next, the remaining Float–Move options are combined with the Infrastructure options to form Float–Move–Infrastructure options (Figure 6.3, step 7);

8. This step creates all possible combination of the remaining combined Float–Move options with the Infrastructure options on an additional sheet within the main spreadsheet. Once again, additional characteristics can now be assessed, including the unallocated weight and volume for each option and the total (UPC) cost of each option. These additional constraints could then be used to assess the options against any remaining requirements in a final down selection phase (Figure 6.3, step 8);

9. Finally, the resulting combined Float–Move–Infrastructure options—which satisfy the specified requirements and constraints—can be examined.

The following two sections present additional details on the actual implementation. Section 6.3 gives details of steps 1-3 while Section 6.4 details steps 4-9.

6.3 Generation of the Exploratory Implementation's Library

This section details the approach taken to generate the data in the exploratory implementation's library. An example of the library generation process can be found in Section D.1 of Appendix D.

Using the breakdown from Table 6.1 the different functional group options were generated by adapting the equations used in the UCL MSc Ship Design Exercise [UCL 2002, 2004]. The calculations used are described in Sub-sections 6.3.1 to 6.3.3. Some data sources were common between the functional groups; weight and volume data used in the model were derived from the UCL MSc Ship Design Exercise. These data sources present weight and volume information in terms of a seven group weight breakdown structure (WBS), similar to the UK MoD WBS, therefore it was necessary to map this to the four group functional breakdown. Table 6.1 shows the relationship between the seven WBS groups and the functional groups.

Table 6.1: Breakdown of UCL Weight Groups to Functional Groups

Weight Group	Description	Functional Group
Group 1	Hull	Float
Group 2	Personnel	Infrastructure
Group 3	Ship Services	Infrastructure
Group 4	Main Propulsion	Move
Group 5	Auxiliary Electrical Power	Infrastructure
Group 6	Combat Systems	Operations
Group 7	Variables	Move and Operations

As stated in Chapter 5, for this limited demonstration the decision has been made to limit the options developed in each group to a single ship style. Thus Float sub-options are limited to a monohull hullform, the Move sub-options are limited to a direct drive transmission system and the Infrastructure sub-options represent a limited range of naval ship accommodation and service systems definitions. This is a significant limitation for this specific implementation of the Library Based approach. However, the implementation presented here could be extended to accommodate additional styles, if suitable tools were made available to generate options and a suitable library structure existed to store the data. An implementation able to demonstrate more of these features is presented in the following chapter.

6.3.1 Generating Float Functional Group Sub-Options

For the Float functional group, sub-options were generated from six input variables: displacement (Δ), overall hull density (ρ), hull depth (D), block coefficient (C_B), allowable vertical centre of gravity (KG) and superstructure volume fraction (vs). The values of these variables were selected randomly, but each was constrained to lie within a specific range (e.g. the displacements considered ranged from 3500-6000te). From these six variables the values of the remaining significant hullform characteristics could be determined by applying standard hydrostatic and stability considerations. From these characteristics, values for the weight (W_{float}), volume (V_{float}) and procurement cost (C_{float}) of each Float functional group option were found using the adapted MSc Ship Design Exercise equations [UCL 2004]. With the hullform's characteristics now fixed two performance analysis methods were applied; the required power for a number of speeds was determined using the Holtrop resistance predication method [Holtrop 1984] and an estimate of the hullform's seakeeping performances was found using Bales seakeeping rank method [Walden 1983]. The flow of computation of these variables, through the calculation of Float sub-option's characteristics, is shown in Figure 6.4.

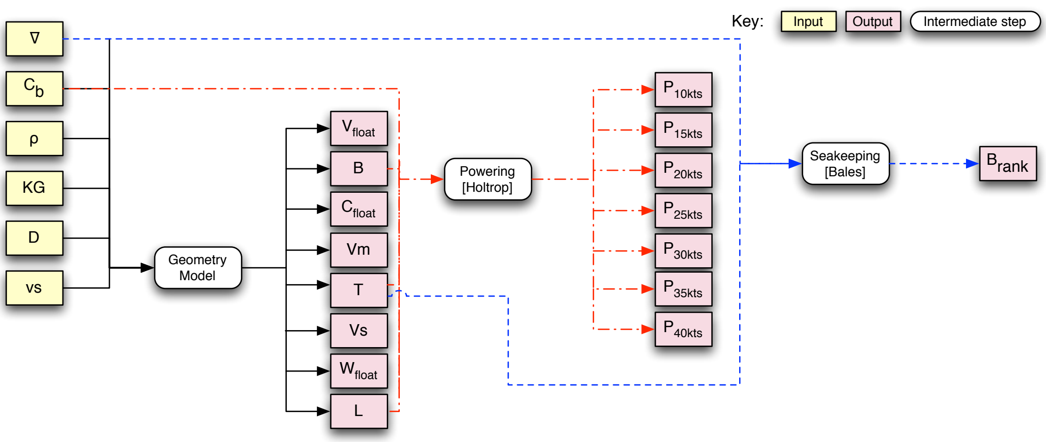


Figure 6.4: Flow of Variables in the Calculation of Float Function Sub-Option Properties for the Exploratory Implementation of the Library Based Design Approach

6.3.2 Generating Move Functional Group Sub-Options

For the Move functional group the sub-options were generated from three input variables: two of these variables defined the sub-option's two prime movers (from twelve possible alternatives) and a third variable defined the amount of fuel carried. Each complete Move functional option was developed using the assumption that the propulsion train was constrained to consist of two propellers driven via appropriately sized reduction gearboxes. The data used to generates these options was based upon that available from commercial sources and UCL [2004]. From these three variables the following data was obtained: weight (W_{move}), volume (V_{move}), procurement cost (C_{move}) and values of power and specific fuel consumption at different machinery loads. The flow of computation of these variables, through the calculation of Move sub-option's characteristics, is shown in Figure 6.5.

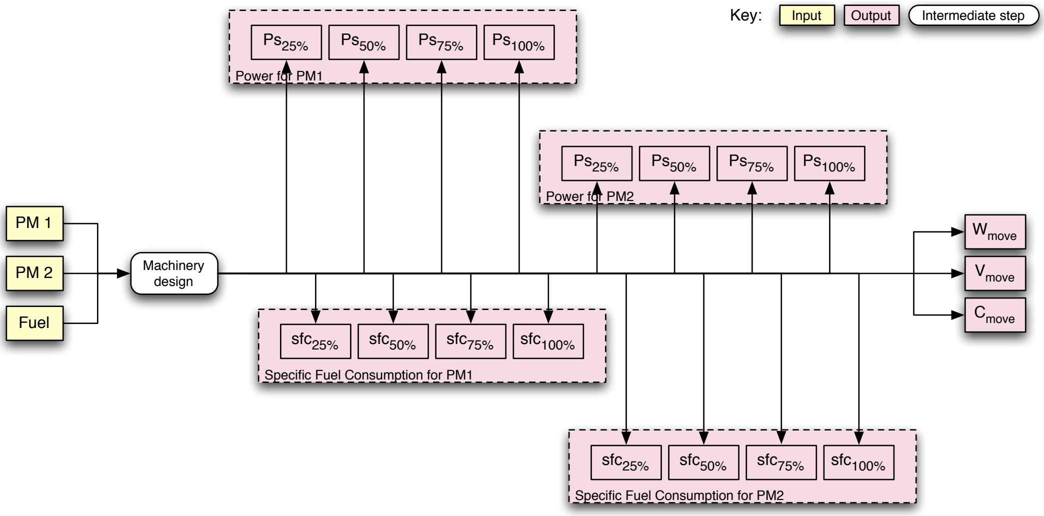


Figure 6.5: Flow of Variables in the Calculation of Move Function Sub-Option Properties for the Exploratory Implementation of the Library Based Design Approach

6.3.3 Generating Infrastructure Functional Group Sub-Options

For the Infrastructure functional group the sub-options were generated from input variables describing the number of crew and a required stores endurance in days. The sizing equation also required a value of the ship's net volume (representing the ventilated space within the ship), for simplicity this was assumed constant for the purpose of this demonstration; by adding an additional input variable, different values of net volume could be easily considered. From these variables values were obtained for the weight (W_{inf}), volume (V_{inf}) and procurement cost (C_{inf}) of the Infrastructure functional group. The flow of computation of these variables, through the calculation of Infrastructure sub-option's characteristics, is shown in Figure 6.6.

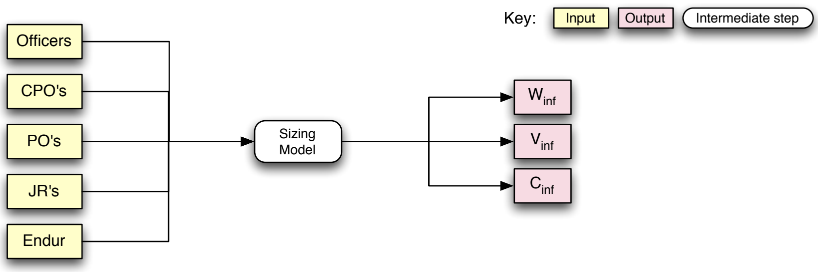


Figure 6.6: Flow of Variables in the Calculation of Infrastructure Function Sub-Option Properties for the Exploratory Implementation of the Library Based Design Approach

6.4 Combination and Down Selection in the Exploratory Implementation

This section outlines the steps shown in detail in Section D.2 of Appendix D.

6.4.1 Float Sub-Options Down Selection

The down selection step for the Float sub-options employs the requirement that can be solely attributed to that sub-option. In this case, four requirements are used:

- Maximum draught;
- Maximum length;
- Maximum beam;
- A power constraint at a speed of interest.

Figure 6.7 shows the effect of these four different requirements in the down selection of the Float sub-options. This figure shows the impact of the sequential down selection steps upon the number of remaining options. Beginning with the sub-option from library the four different requirements removed unacceptable solutions and reduced the number of remaining sub-options.

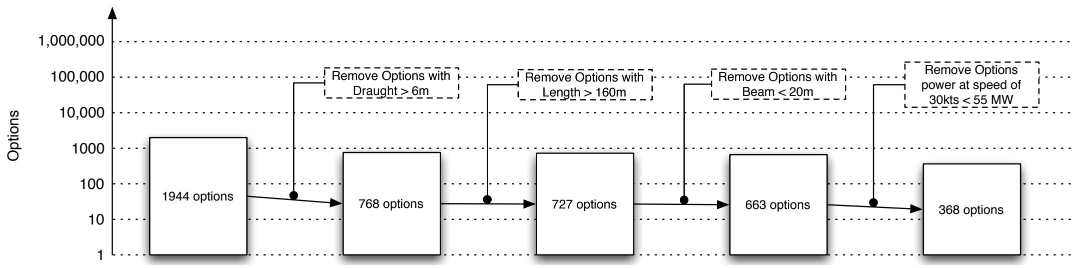


Figure 6.7: Float Sub-Option Down Selection for the Exploratory Implementation of the Library Based Design Approach

6.4.2 Move Sub-Options Down Selection

The down selection step for the Move sub-options employs the requirement that can be solely attributed to the sub-option. In this case, two requirements are used:

- Maximum ship procurement cost[1];
- Maximum installed power.

Figure 6.8 shows the effect of these two different requirements for the down selection of the Move sub-options.

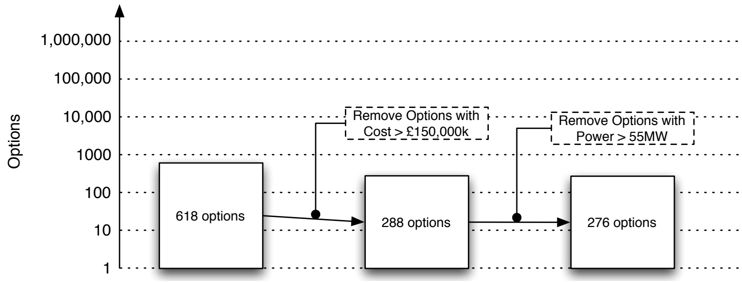


Figure 6.8: Move Sub-Option Down Selection for the Exploratory Implementation of the Library Based Design Approach

6.4.3 Infrastructure Sub-Options Down Selection

The final set of functional group down selection are for the Infrastructure sub-options and employ the following two requirements:

- Minimum endurance;
- Minimum complement of officers[2].

Figure 6.9 shows the effect of these two requirements in the down selection of the Infrastructure sub-options.

[1] As the cost any acceptable Move sub-option cannot exceed the total procurement funds available for the overall ship.

[2] This requirement is intended to be indicative of the minimum crew required to operate both the combat systems and other key vessel systems.

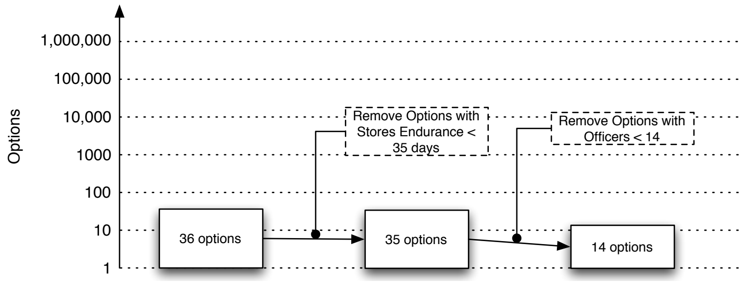


Figure 6.9: Infrastructure Sub-Option Down Selection for the Exploratory Implementation of the Library Based Design Approach

6.4.4 Combination of Float and Move Sub-Options

After the functional group sub-options have been down selected, the remaining option are combined. Figure 6.10 shows the steps involved in combining any two Float and Move sub-options.

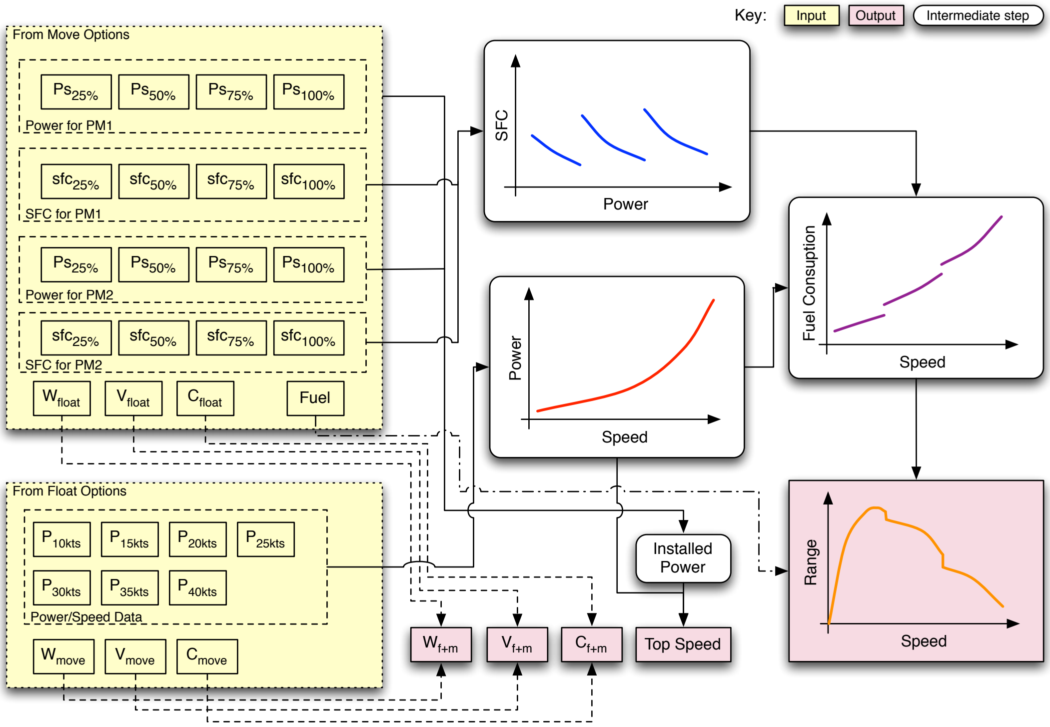


Figure 6.10: Combination of Float and Move Sub-Options for the Exploratory Implementation of the Library Based Design Approach

The Move sub-options contain information on the power output and fuel consumption of each option's prime movers. This data represents the most fuel efficient combination of prime movers over the range of available powers. The Float sub-options contain information that gives a relationship between speed and a requires propulsive power derived from each vessel's resistance. For any specific combination of Float and Move sub-options this data can be used to determine the following important performance characteristics for the combined option:

- Top speed (from the Move sub-options maximum propulsive power and the Float options speed–power data);
- Fuel consumption with speed (from the Move sub-options fuel consumption–power and the Float options speed–power data);
- Maximum range at each operating speed (using the fuel capacity of the Move sub-option and the Fuel consumption with speed data of the combined option).

Additionally, the following three combined option characteristics are found by totalling the appropriate sub-option characteristics:

- Weight;
- Volume;
- Procurement cost.

6.4.5 Float–Move Combined Options Down Selection

Once the combined options are developed a new set of down selection criteria are employed to remove unacceptable options. The following requirements are used in this down selection:

- Minimum range at a specified speed;
- Minimum top speed.

Figure 6.11 shows the effect of four speed and range requirements in the down selection of a number of combined options. Other requirements (such as a maximum permissible procurement cost) could also have been applied at this point.

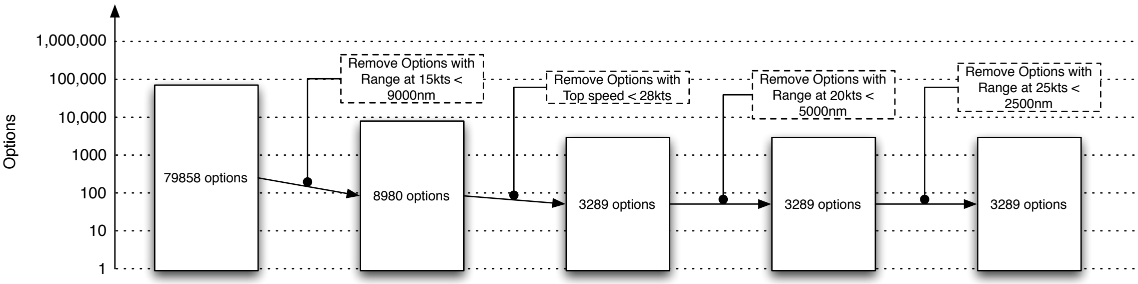


Figure 6.11: Float–Move Combined Option Down Selection for the Exploratory Implementation of the Library Based Design Approach

6.4.6 Combination of Float–Move and Infrastructure Options

The final step consists of developing combined Float–Move–Infrastructure options from the Infrastructure sub-options and the combined Float–Move options. Figure 6.12 shows an overview of this step. In the case of this demonstration the options are simply combined and the overall totals found for the following three key characteristics:

- Weight;
- Volume;
- Procurement cost.

Other characteristics that could have been assessed include a comparison between the crew number assumed for the Infrastructure sub-options and the crew number demand for each of the Float and Move sub-options.

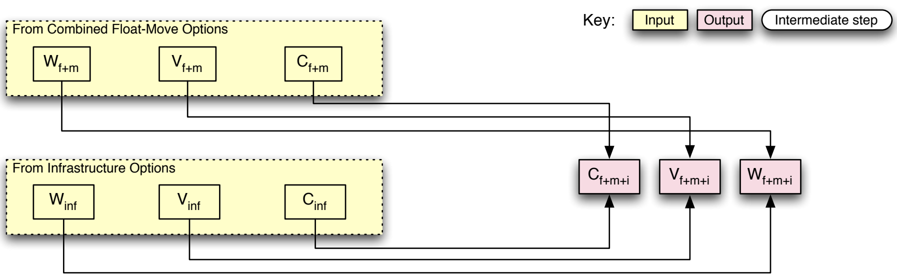


Figure 6.12: Combination of Float–Move Combined Options with Infrastructure Sub-Option for the Exploratory Implementation of the Library Based Design Approach

6.4.7 Float–Move–Infrastructure Combined Options Down Selection

Once the combined options are developed a final set of down selections are employed to remove unacceptable options. The following three requirements are used in this down selection:

- Unallocated weight;
- Unallocated volume;
- Total procurement cost.

The unallocated weight and volume required in the design were estimated from the vessel's combat system and their associated variables. Figure 6.13 shows the effect of these requirements for the down selection of the final Float–Move–Infrastructure combined options.

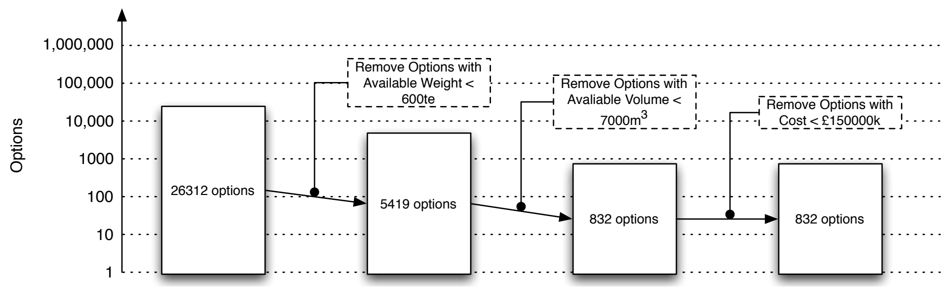


Figure 6.13: Float–Move–Infrastructure Sub-Option Down Selection for the Exploratory Implementation of the Library Based Design Approach

6.5 Case I: Cassard Requirements

The first design selected for comparison was the French Navy's Cassard Class Destroyers (Type F70 – DDGHM) [Janes 2003]. This design is referred to in this section as the 'Cassard' design. As only a limited amount of information is available via public sources [Janes 2003] some of the ship's characteristics were estimated using ratios derived from similar ships [Brown and Andrews 1980; UCL 2002]. Detailed specification for this design are provided in Figure E.2 in Appendix E.

Table 6.2 summarises the requirements derived from the information on the 'Cassard' design. These requirements were applied when using the Library Based tool described in Section 6.2. The Library Based tool employed a library of sub-options as described in Section 6.3. Using these sub-options and the requirements from the Cassard design the exploratory implementation was used to evaluate the options remaining as the down selection and combination process progressed. Table 6.2 summarises the number of options remaining after each down select operation.

6.5.1 Results

Four different figures have been selected to show how the number of acceptable options change through the process described in the previous section, progressing from figures which present the Float sub-option characteristics through to figures presenting the combined whole ship option characteristics.

Figure 6.14 shows the displacement and length of all the generated solutions and for the 'Cassard' design itself. In terms of the functional breakdown, displacement and length are purely Float characteristics. The small number of points on this graph is due to only a limited number of the original Float options being able to fulfil the complete set of requirements. Figure 6.14 shows that the original 1944 Float options have been reduced down to 152 acceptable solutions by the three subsequent down selection steps. This compares with the 368 Float sub-options that remained after the initial Float down selection. The difference can be attributed to the removed of all combined Float–Move or Float–

Table 6.2: Requirements Applied for the Cassard Design from the Case I Design Study

Function	Requirement			Options Remaining
Float	Draught	$<$	6 m	768
	Length	$<$	160 m	727
	Beam	$<$	20 m	663
	Power at 30 knots	$<$	55 MW	368
Move	Procurement Cost[a]	$<$	£150,000k	616
	Maximum Power	$<$	45 MW	476
	Minimum Power	$>$	25 MW	224
Infrastructure	Stores Endurance	$>$	35 days	18
	Number of Officers	$>$	14 men	8
Combined Float–Move	Range at 15 knots	$>$	11,500 nm	4277
	Top Speed	$>$	29.5 kts	783
	Range at 20 knots	$>$	5000 nm	783
	Range at 25 knots	$>$	2500 nm	783
Combined Float–Move–Infrastructure	Unallocated[b] weight	$>$	330 te	4686
	Unallocated[c] volume	$>$	2160 m^3	4385
	Cost	$>$	£150,000k	4378

[a]Note that this excludes the cost attributed to the Operations functional group.
[b]This refers to the unallocated weight available for the combat system and its associated variables.
[c]This refers to the unallocated volume available for the combat system and its associated variables.

Move–Infrastructure options that contained these Float sub-options during the later down selections. The point representing the ‘Cassard’ design can be seen to lie in the centre of these remaining points.

Next, Figure 6.15 shows the different solutions’ top speeds and the solutions’ endurance in terms of nautical miles at a speed of 15kts. The point representing the ‘Cassard’ design can be seen to lie at the bottom left corner of the points representing the solutions. This is expected as two of the requirements used to down select these solutions were a requirement to provide a maximum speed of at least 29.5 knots and a range of 11500nm at a speed of 15 knots, requirements which are equivalent to the published performance of Cassard Class ships.

Finally, Figures 6.16 and 6.17 show characteristics of the complete ship solutions. In these two charts the unallocated weight and volume are plotted against the combined procurement cost of the solution’s Float, Move and Infrastructure groups. The point representing the ‘Cassard’ design can be seen to lie on the limit of the points representing the generated solutions, in this case at the left of the solutions shown in Figures 6.16 and 6.17. This indicates that the actual ‘Cassard’ design has unallocated space and weight

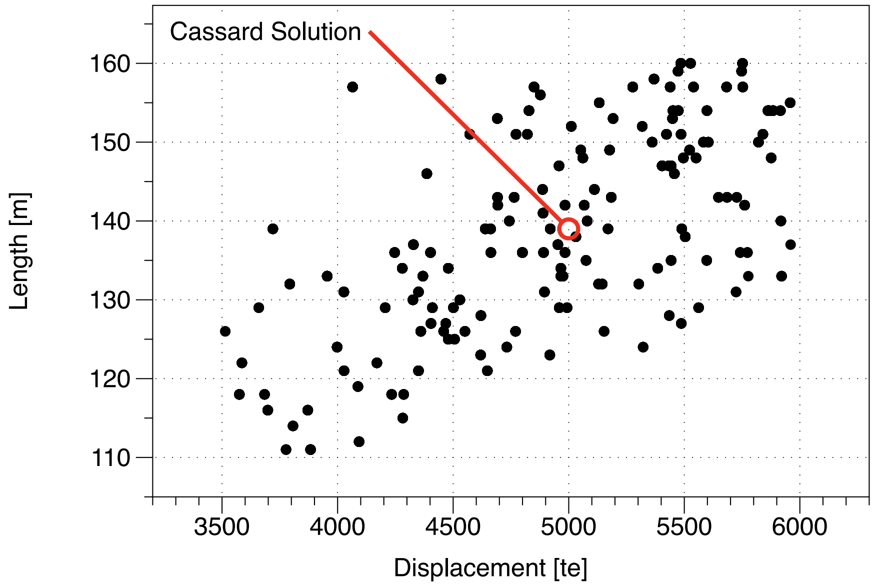


Figure 6.14: Displacement and Length of Acceptable Solutions and the Cassard Design from the Case I Design Study

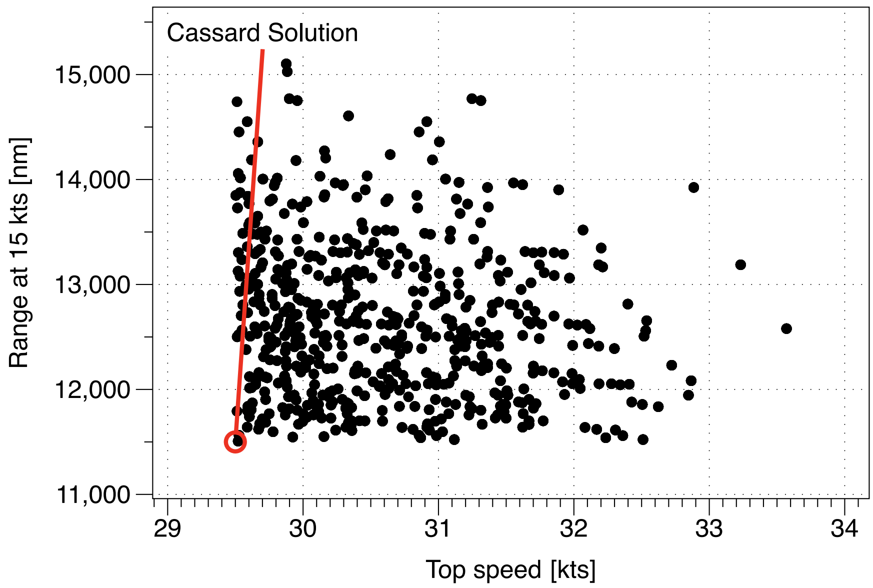


Figure 6.15: Top Speed and Range of Acceptable Solutions and the Cassard Design from the Case I Design Study

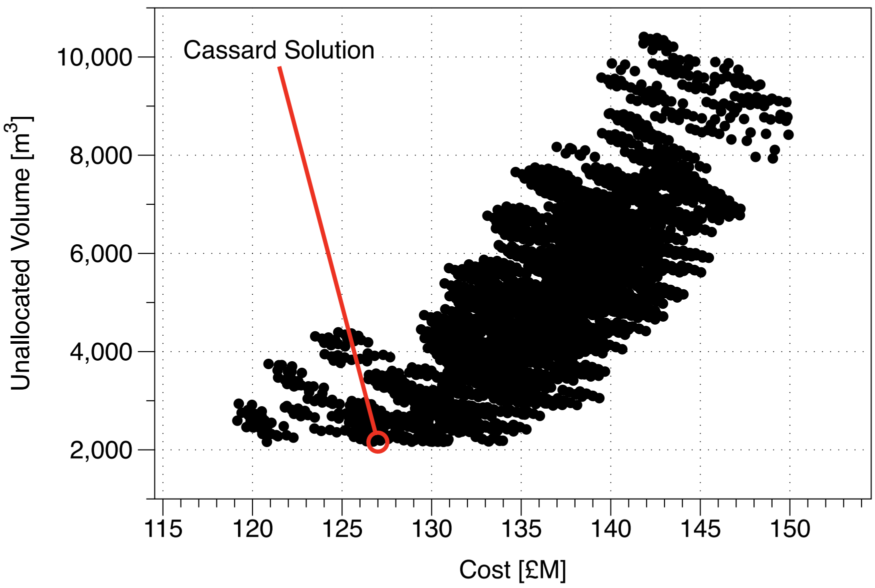


Figure 6.16: Unallocated Volume vs. Cost of Acceptable Solutions and the Cassard Design from the Case I Design Study

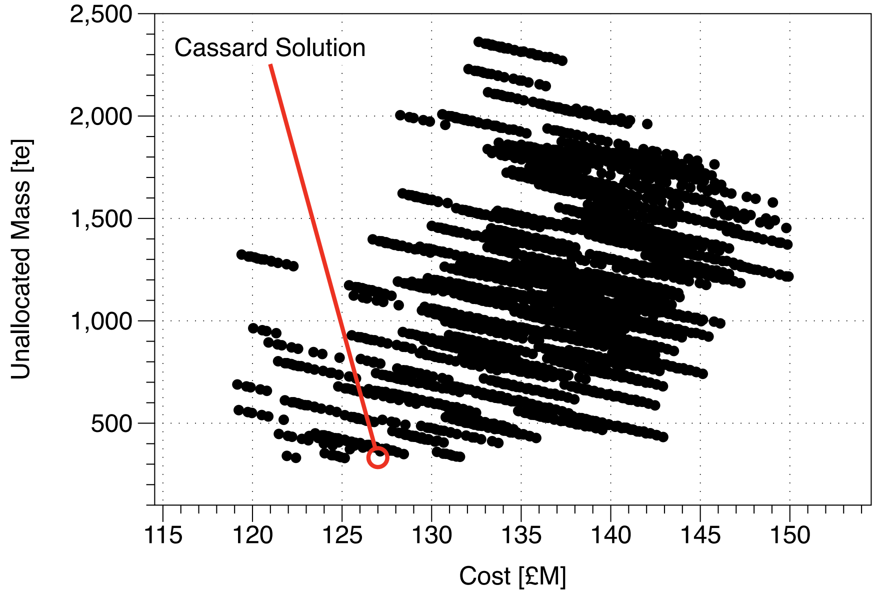


Figure 6.17: Unallocated Weight vs. Cost of Acceptable Solutions and the Cassard Design from the Case I Design Study

sufficient to accommodate the fitted operations related systems and is, therefore, a weight and space balanced design.

6.5.2 Run Times

An important consideration of any ship concept design tool is the speed of execution. Table 6.3 summarises the requirements applied when using the tool. The code was run on a 2.13 GHz Dell Precision M70 laptop with 2 GB of RAM.

Table 6.3: Run times for Cassard Case using the Exploratory Implementation from the Case I Design Study

Step	Duration (hrs:min:sec)
Generate Float Sub-Options	02:55:36
Generate Move Sub-Options	02:21:15
Generate Infrastructure Sub-Options	00:01:19
Down select Float Sub-Options	00:00:09
Down select Move Sub-Options	00:00:02
Down select Infrastructure Sub-Options	00:00:04
Combine Float and Move Sub-Options	01:45:49
Down select Combined Float–Move Options	00:07:54
Combine Float–Move and Infrastructure Options	00:09:25
Down select Float–Move–Infrastructure Options	00:02:18
Total	07:23:52

Referring to the run times listed in Table 6.3, it is apparent that the majority of the execution time is related to the generation of the Float, Move and Infrastructure sub-options. In total over five hours was required to generate the sub-options for the three functional groups. However, the down selection and combination steps still required over two hours to develop the set of acceptable Float–Move–Infrastructure combined options.

6.6 Case II: SDE 2007 Requirements

The second set of requirements were derived from a previous UCL design [Riaz et al. 2007]. This design was chosen at random from the catalogue of monohull warship ship designs previously developed by MSc students during the UCL Ship Design Exercise while being comparable to the 'Cassard' design; it is termed the 'SDE 2007' design. A specification for this design is provided in Figure E.1 in Appendix E.

Table 6.4 show the sixteen different requirements applied during the examination of the SDE 2007 case. As with Section 6.5, these were applied using the Library Based tool described in Section 6.2 which employed a library of sub-options as described in Section 6.3. This implementation was used to evaluate the options remaining as the down selection and combination process progressed. Table 6.4 also displays the number of options remaining under consideration during each of the down select steps.

Table 6.4: Requirements Applied for the SDE 2007 Design from the Case II Design Study

Function	Requirement			Options Remaining
Float	Draught	$<$	6 m	768
	Length	$<$	160 m	727
	Beam	$<$	20 m	663
	Power at 30 knots	$<$	55 MW	368
Move	Cost[3]	$<$	£150,000k	616
	Maximum Power	$<$	45 MW	476
	Minimum Power	$>$	25 MW	224
Infrastructure	Stores Endurance	$>$	35 days	18
	Number of Officers	$>$	14 men	8
Combined Float–Move	Range at 15 knots	$>$	9000 nm	8980
	Top Speed	$>$	28 kts	3289
	Range at 20 knots	$>$	5000 nm	3289
	Range at 25 knots	$>$	2500 nm	3289
Combined Float–Move–Infrastructure	Unallocated[4] weight	$>$	640 te	5419
	Unallocated[5] volume	$>$	7350 m^3	832
	Cost	$>$	£150,000k	832

6.6.1 Results

Once again four figures are selected to show how the number of acceptable options change through the process described in the previous section, progressing from Figure 6.18 which presents the Float sub-option characteristics through to Figure 6.21 which presents the combined whole ship option characteristics.

Figure 6.18 shows the displacement and length of both the generated solutions and the SDE 2007 design. As before, there are only a small number of points on this graph because only a limited number of the original float options fulfil the complete set of requirements. Figure 6.18 shows that the original 1944 Float options have been reduced down to 14 acceptable options by the three subsequent down select steps. The point representing the SDE 2007 design can be seen to lie in the centre of these points.

Next, Figure 6.19 shows the different options' top speeds and the options' endurance in terms of nautical miles at a speed of 15kts. The point representing the SDE 2007 design

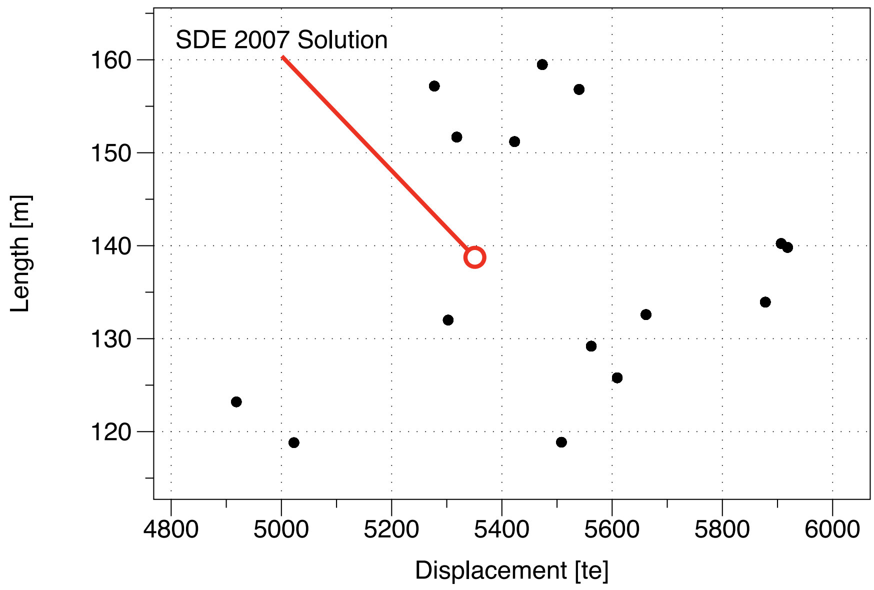


Figure 6.18: Displacement and Length of Acceptable Solutions and the SDE 2007 Design from the Case II Design Study

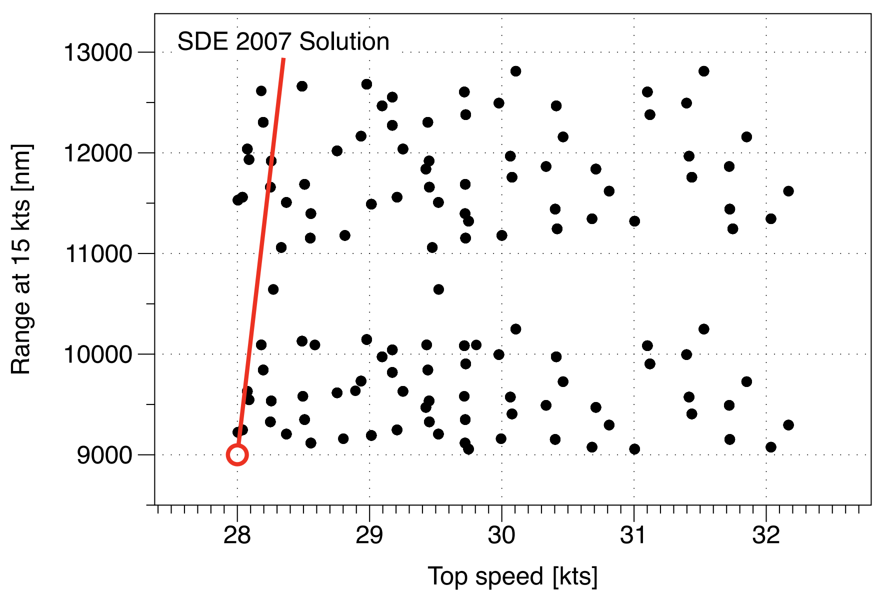


Figure 6.19: Top Speed and Range of Acceptable Solutions and the SDE 2007 Design from the Case II Design Study

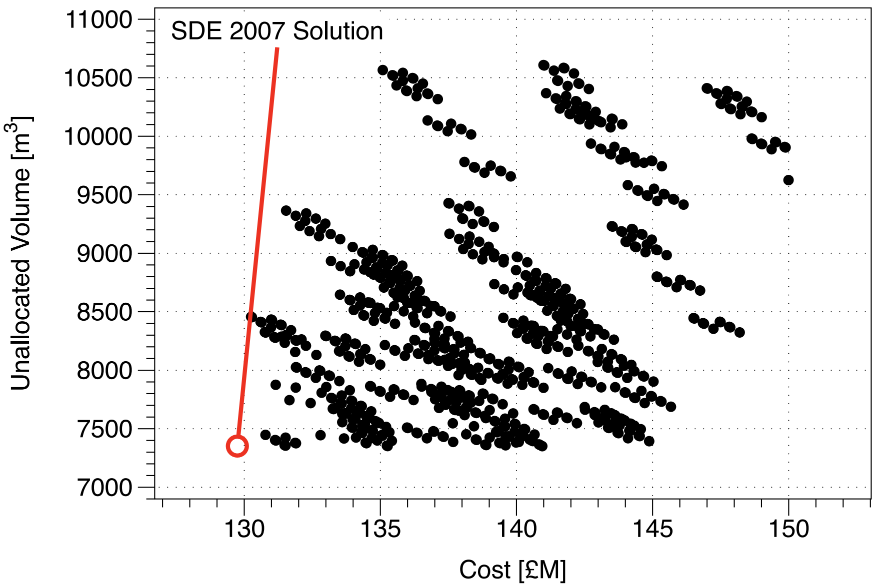


Figure 6.20: Unallocated Volume vs. Cost of Acceptable Solutions and the SDE 2007 Design from the Case II Design Study

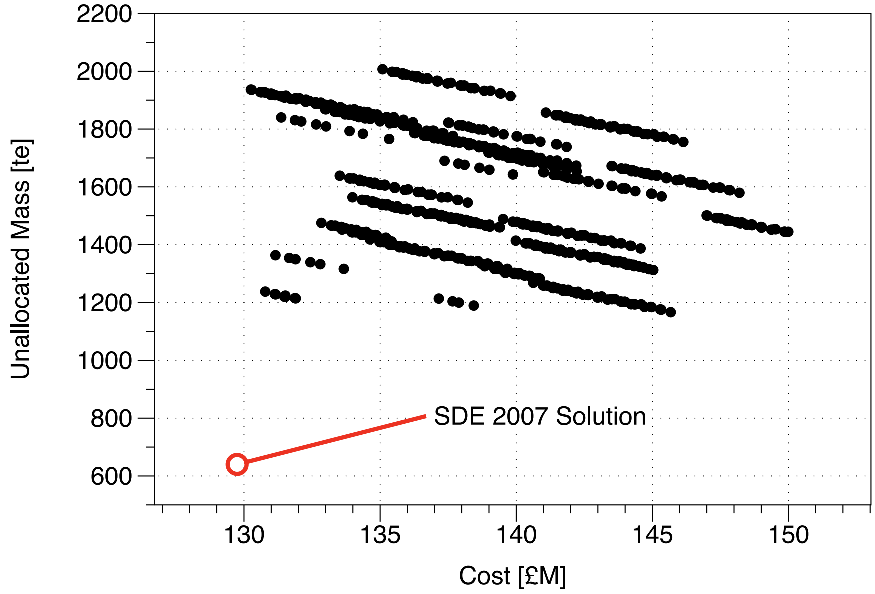


Figure 6.21: Unallocated Weight vs. Cost of Acceptable Solutions and the SDE 2007 Design from the Case II Design Study

can be seen to lie at the one edge of the points representing the options. This is expected as one of the requirements used to down select these options was a requirement to provide a maximum speed of at least 28 knots and the SDE 2007 design just achieves this speed.

Finally, Figures 6.20 and 6.21 show characteristics of the complete ship options. In these two charts the unallocated weight and volume are plotted against the combined cost of the options Float, Move and Infrastructure groups. The point representing the SDE 2007 design can be seen to lie some distance from the points representing the generated options. The difference between the SDE 2007 design and the generated options can be explained in terms of significant technical differences in the Move functional group between the SDE 2007 design and the options generated here.

Section 6.3 explained how the Move functional group sub-options were generated based upon the assumption that the propulsion train consisted of two propellers driven by gas turbines or diesel engines via reduction gearboxes. This was complemented by a number of diesel generator that provided an appropriate hotel load. In comparison, the SDE 2007 design made use of a far heavier integrated full electric propulsion (IFEP) system composed of four prime movers. The generated Move options match the IFEP systems performance in terms of the limited requirement considered in this case; principally, the power for the required top speed and endurance for the required range at a cruise speed. However, one common reason for the adoption of IFEP propulsion systems is their efficiency over a large range of propulsive and hotel loads [Hodge and Mattick 1996]. If these demands were included in the requirements the remaining Move functional group solutions would be more complex, larger and expensive; therefore, closer to the characteristics of SDE 2007 design propulsion system. Alternatively, if the library was supplemented by additional Move options describing IFEP machinery configurations, a design similar to the SDE 2007 design would emerge as an alternative solution.

6.6.2 Run Times

As with the 'Cassard' design example presented in Section 6.5.2, the run times obtained when using the exploratory implementation to examine the SDE 2007 requirements are found in Table 6.5. Table 6.5 summarises the requirements applied when using the tool. The code was run on a 2.13 GHz Dell Precision M70 laptop with 2 GB of RAM.

As with the first application of the exploratory implementation, discussed in Section 6.5, the majority of the run time for this case is associated with the generation of Float, Move and Infrastructure sub-options. However, a significant amount of time is still needed to complete the down selection and combination steps (as in the earlier case over two hours) before the final combined options are obtained.

Table 6.5: Run times for SDE 2007 Case using the Exploratory Implementation from the Case II Design Study

Step	Duration (hrs:min:sec)
Generate Float Options	02:54:51
Generate Move Options	02:20:52
Generate Infrastructure Options	00:01:18
Down select Float Options	00:00:09
Down select Move Options	00:00:02
Down select Infrastructure Options	00:00:04
Combine Float and Move Options	01:43:28
Down select Combined Float–Move Options	00:07:22
Combine Float–Move and Infrastructure Options	00:08:49
Down select Float–Move and Infrastructure Options	00:02:09
Total	07:19:04

6.7 Discussion

This chapter has illustrated the key processes of the proposed method via an exploratory implementation. The different steps within the method have been clearly outlined, using a simple monohull ship as an example case. Section 6.3 detailed the first step within the method, the generation of a library of functional group sub-options. The inputs and calculations used to synthesis the Float, Move and Infrastructure functional group sub-options were described in depth. This section clearly demonstrated how these functional group sub-options can be developed based upon a small number of input variables. Furthermore, the implementation showed that analysis methods can assess the sub-option's performance (e.g. calculating the resistance and hence the required propulsive power). This demonstrated that is possible to take an existing synthesis method (such at that employed in the UCL MSc Ship Design Exercise [UCL 2002, 2004]) and reformulate this in terms of a number of functional groups. After this step, Section D.2 described how the generated sub-option were down selected, using representative criteria and requirements, to remove unacceptable sub-options from consideration. This process demonstrated that requirements (representative of a set of customer needs) can be used in the down selection of sub-options from each functional groups. Next, the remaining sub-options were combined, first to form combined Float–Move options, then combined Float–Move–Infrastructure options; during this process additional appropriate down selects were undertaken when possible. By demonstrating that sub-options can be combined and than assessed to find emergent attributes (such as range at specific speed, top speed, unallocated weight, unallocated volume and total cost) the mapping shown in Section 5.3.3 has been justified. Furthermore, the exploratory implementation demonstrated how these emergent attributes can be used, with appropriate requirements derived from customer needs, to down select the combined options. The final set of down selects resulted in a set of combined options able to satisfy the requirements. This process has shown how a wide number of potential options[6] can be explored by down selecting appropriate functional group sub-options and then combining these sub-options to form overall ship options leaving space and volume to meet 'payload' demands.

6.7.1 Comparison with Other Designs

In general, there is good agreement between the options developed using this method and point designs produced using alternative methods, as shown in Figures 6.14–6.21. For the two example designs at both the Float and the combined Float–Move functional group level the proposed options also show close agreement with the designs produced using alternative methods. However, there were more significant differences for the combined solutions in the case of the SDE 2007. The origin of these differences was identified in Section 6.6 as being due to the differing propulsion system style the SDE 2007 design adopted (integrated full electrical propulsion) compared to style of the Move sub-options stored within the library (conventional mechanical transmission). The scale of this difference demonstrates how a change in the style of one element of the proposed options can lead to a radical change in the options available, for a given set of requirements or constraints.

6.7.2 Technical Implementation

As discussed in Section 6.2.1, the exploratory implementation uses Microsoft Excel in combination with Microsoft Visual Basic. This combination was selected due to the simple, flexible development environment that it provided for an exploratory implementation. However, for the library used in Cases I and II the main spreadsheet containing the design data grew to over 100MB in size by the end of the run. As a consequence, the implementation was both slow to use, as shown by Tables 6.5.2 and 6.5, and difficult to modify[7]. This may create an impediment to the use of the exploratory implementation as a design tool during the early concept design process.

These problems are a result of the procedural, scalar programming language and single file based storage format which underpin this model. In the exploratory approach each step of the implementation takes the form of an operation on a single row of data within

[6] In this case 43,250,112 potential combined options that could have been generated by combining the 1944 Float sub-options, 618 Move sub-options and 36 Infrastructure sub-options.

[7] While a brief attempt was made to extend the exploratory implementation to assess multiple hullform style this was quickly realised to be a significant task that would have required the exploratory implementation to be almost totally rebuilt.

the spreadsheet. For example, when performing the down selection process the code must examine each row of the spreadsheet against a number of conditions (i.e. has the row already been removed from consideration, does it meet the current criteria). Additionally, there is significant data replication between portions of the spreadsheet's rows (i.e. the combination step results in each of the sets of data representing each functional group options being copied to many rows on a different sheet). Procedural and scalar programming methods offer little assistance with these data management tasks. Further improvement of the speed and flexibility is viewed as being important to demonstrate the feasibility of a Library Based ship approach for practical concept design applications where, as already remarked, rapid response is required.

6.8 Conclusions on the Exploratory Implementation

This chapter presented the first (exploratory) implementation of the proposed Library Based ship concept design tool. This implementation has demonstrated that by applying a combination type operation it is possible to explore potential options. The designs produced by the exploratory implementation correlated well with two point designs produced by other methods. Sections 6.5 and 6.6 have compared the options generated by the exploratory implementation to two independently developed designs and thus demonstrated that the generated options are valid. This initial implementation was found to fulfil the goal set out at the start of this chapter. However, the speed and flexibility of the implementation is viewed as being important to demonstrate the feasibility of the approach to the problem of hullform selection. Chapter 7 will describe an alternative improved implementation that addresses the weaknesses highlighted in this section.

7 An Improved Implementation of the Approach

The previous chapter demonstrated an exploratory implementation of the Library Based ship concept design approach. This implementation explored some of the key issues of the approach but revealed some significant technical weaknesses. This chapter presents a second implementation that addresses these weaknesses. This second tool, termed the 'improved implementation', better supports a Library Based ship concept design approach (as presented in Chapter 5) compared to the exploratory implementation presented in Chapter 6.

Section 7.1 outlines the key aims of the improved implementation. Section 7.2 then discusses the improved implementation that has been developed to satisfy these aims. The improved implementation differs from existing concept design tools in that it adopts a database backed object-oriented programming approach.

Following this description of the tool, two cases of applying the tool are presented:

- Section 7.3 containing Case III, which revisits one of the cases explored in Chapter 6 using the exploratory implementation, to reveal the differences in execution time compared to the exploratory implementation;
- Section 7.4 containing Case IV, which uses the tool to explore a number of alternative hullforms using a library containing several different hullforms and sets of requirements selected from a recent naval ship design programme.

Finally, Sections 7.5 and 7.6 provide a discussion of and conclusions on the improved implementation.

7.1 Aims of the Improved Implementation

The exploratory implementation presented in Chapter 6 revealed a number of limitations specific to that implementation of the Library Based approach to ship concept design. In particular the run times of the exploratory implementation were considered excessive. Furthermore, the exploratory implementation was also deliberately limited to only consider a limited set of the features of the Library Based approach, as presented in Chapter 5.

To address both these issues an improved implementation was developed. The list of aims for the improved implementation are:

- Increased execution speed so the implementation can be used interactively by a designer (with a target of at least halving the execution time);
- Demonstrate the ability to manage designs with different ship hullform styles;
- Demonstrate the ability to build up domain knowledge and implement practical performance prediction methods, thereby demonstrating the practical use of the proposed method.

The next section describes the details of the improved implementation and how it addresses these aims.

7.2 Overview of the Improved Implementation

This section briefly outlines the improved demonstration of the Library Based ship concept design approach. A more comprehensive description of this implementation can be found in Section F.1 of Appendix F. This appendix contains a comprehensive discussion on how the improved implementation works in the following areas:

- Storage of the principal objects in the library (Section F.1.1), particularly how the implementation facilitates the storage of sub-options with differing styles (pp302);
- Performance prediction in the improved implementation using the objects stored within the improved implementation's library (Section F.1.2);
- The actions within the improved implementation that retrieve sub-options from the library and then down select and combine sub-options to create options (Section F.1.3);
- Strategies for down selection and performance predictions that show how a Library Based design tool can be used efficiently (Section F.1.4);
- The improved implementation's ability to support PDI compliance and the different methods by which new data can be added to the library (Section F.1.5);
- The technical details of the improved implementation are provided (Section F.1.6, although complete code listing have not been included in this thesis).

The improved implementation employs a database backed object-oriented programming approach to rapidly explore options representing a range of alternatives stored in the library. Adopting a database storage system enables the down selection process to make use of the database's rapid search and query capabilities. Options returned by the database can then be realised as instances of objects within the implementation.

The specific implementation discussed in this chapter is constructed using a number of different objects that act together to create a data model able to perform the key tasks outlined in Sections 5.2 and 5.3 of Chapter 5. The seven primary types of objects that make up the improved implementation are illustrated in Figure 7.1 by boxes. This shows each object's attributes (the variables stored within the object) and the relationships the object has to other objects in the library. Of the lines linking the seven primary objects boxes, those terminating with two single arrows denote a one–to–one relationship. A line terminating in one single arrow and one double arrow denote a one–to–many relationship. Finally, a line terminating in two double arrows denote a many–to–many relationship. For example, an Item object may contain relationships linking it to a number of Characteristic objects while each Characteristic object can only be related to a single Item object, this relationship can be defined as a one–to–many relationship. This description of the objects with relationships allows the objects within the library to be mapped to a relational database structure, which enables storage and rapid retrieval, for a given set of constraints.

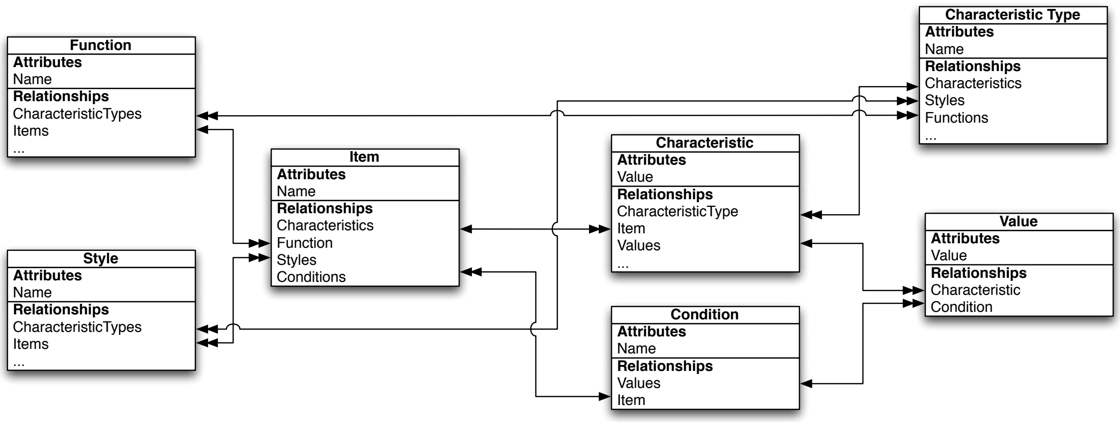


Figure 7.1: Key Objects within the Library

The process of searching the library for appropriate sub-options and combining these to form new options, which are then presented to the designer, is performed by a number of Actions. Actions are split into two types: Fetch Actions that retrieve options from the library and Combine Actions that generate new options by combining sub-options belonging to a number of input actions. These two types can be combined into a hierarchical tree of Actions with Combine Actions as branches and Fetch Actions as leaves, as shown in Figure 7.2. This differs from the iconic representation, shown in Figure 5.9 (on page 136) as a two stage combination process is employed to develop combined Float-Move options and then combined Float-Move-Infrastructure options.

As highlighted in Section 7.1 one of the aims of the improved implementation was to increase the execution speed compared to the exploratory implementation presented in Chapter 6. Section F.2 of Appendix F contains an exploration of the implementation's performance using a set of simple test data.

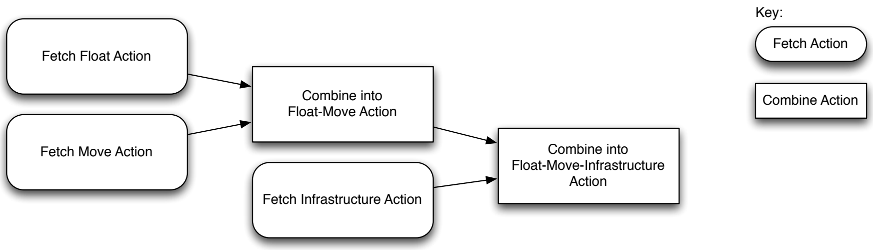


Figure 7.2: Example Hierarchical Tree of Fetch and Combine Actions for the Improved Implementation of the Library Method

7.3 Case III: Revisiting the Exploratory Implementation

Initially, the improved implementation was tested using data generated during the exploration of the initial implementation, as described in Chapter 6, specifically Case I described in Section 6.5. The case presented in this section formed the basis of a recent paper [McDonald and Andrews 2009], which has been included in this thesis as Appendix G.

7.3.1 Library Data Creation

The Library data was created using the simple relationships described in Section 6.3, that were derived from the guidance provided to the UCL students undertaking the Ship Design Exercise that forms part of the MSc in Naval Architecture [UCL 2002, 2004]. These relationships were used to produce several point designs for Float, Move and Infrastructure sub-options. The method used to generate these sub-options matched that described in Section 6.3. Using these methods 1989 Float, 616 Move and 36 Infrastructure sub-options were generated and successfully imported into an empty library[1].

A new Item object was then created in the library to representing each Float, Move and Infrastructure sub-option. Each Item was allocated a function and style, available functions were 'Float', 'Move' and 'Infrastructure', available styles were monohull hullform (Monohull), simple direct drive machinery (Simple_DD) and basic naval ship (Basic_Naval). Next, the newly created Item was allocated several Characteristic objects to retain the values of the sub-option characteristics. The Characteristic objects and their values matched the characteristics developed using the method outlined in Section 6.3.

7.3.2 Down select Steps in the Exploratory Implementation

With the library created, the down select steps described in Section D.2 of Appendix D could now be replicated in this model. Once again, the functional group breakdown was

[1] While, the method used to generate the sub-options matched that from Section 6.3, the numbers of sub-options imported into the improved implementation differ slightly from those given in Section 6.4. A very small number of the sub-options failed to import correctly due to minor data formatting error.

adopted enabling the sub-options in the different functional groups to be first examined independently. Acceptable sub-options were then combined to form whole ship options and the resulting whole ship options were checked to ensure they met all ship requirements specified at the start of the design investigation (following the same broad procedure as the examples from Chapter 6), both those defined by the ship's required performance and those arising from the 'payload'. The steps undertaken were:

- Fetch the Item objects from the library that represent the functional group sub-options, using a subset of the requirements;
- Down selection of the sub-options for each functional group using designer selected criteria derived from requirements (e.g. Float sub-option's draught $<$ 6m);
- Combine acceptable Float and Move options to create Float-Move combined options;
- Down selection of Float-Move combined options using designer selected criteria derived from requirements (e.g. Float-Move combined option's range at 15 knots $>$ 11,500nm);
- Combine remaining Float-Move combined options with Infrastructure options to form Float-Move-Infrastructure combined options;
- Down selection of Float-Move-Infrastructure combined options using designer selected criteria derived from requirements (including payload/operations requirements) to give the final whole ship options (e.g. Float-Move-Infrastructure combined option's cost $<$ £150m).

The steps listed above were defined as several Actions within the implementation. The flow of information between these Actions is shown in Figure 7.3. The different Actions are denoted in the figure by the boxes with bevelled corners.

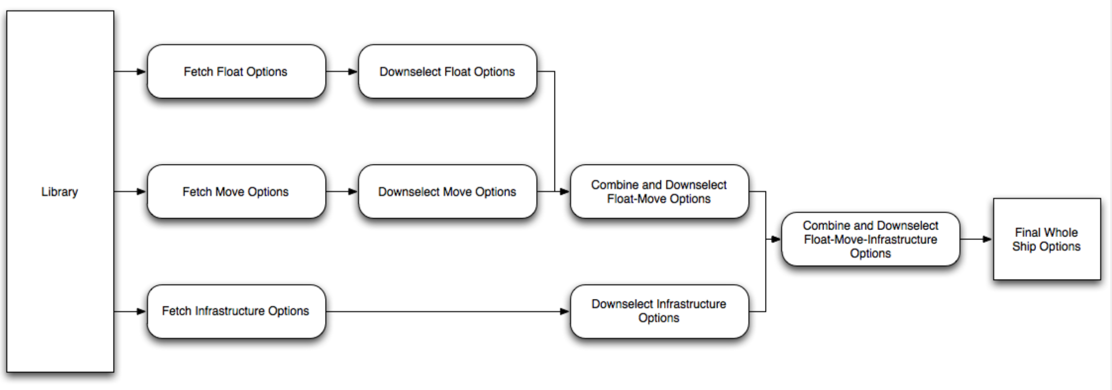


Figure 7.3: Flow of Information between the Steps in the Design Method applied to Case III using the Improved Implementation

Fetch Action for Retrieving Float Sub-Options, Move Sub-Options and Infrastructure Sub-Options

The first step in the solution process involved retrieving the Items representing the Float functional group sub-options from the library. The 1898 Float sub-options in the library were retrieved and down selected using several input requirements. The requirements used in the example for this down selection were:

- Draught $<$ 6m;
- Length $<$ 160m;
- Beam $<$ 20m;
- Power at a Speed of 30kts $<$ 55MW.

From the 1898 Float functional group sub-options contained within the library only 476 sub-options satisfied these requirements. Fetching the sub-options from the Library took 0.16 seconds while down selecting to find acceptable solutions requires 6.14 seconds. A similar approach was adopted to retrieve sub-options from the library from the Move and Infrastructure functional groups. For the Move functional group 616 sub-options stored in the library were down selected to give 544 remaining sub-options, fetching these sub-options from the Library took 0.11 seconds while down selecting the acceptable solutions required 1.93 seconds. Similarly, for the Infrastructure functional group 36 sub-options stored in the library were down selected to give 8 remaining sub-options, fetching these sub-options from the Library took 0.03 seconds while down selecting the acceptable solutions took less than 0.01 seconds.

Combine Action to create Combined Float-Move Options from Float and Move Options

Next, all possible combinations of the remaining Float and Move sub-options were then generated. In the case of this implementation, simple additional calculations were used to assess the maximum speed and a speed-range profile. This combination of 476 Float group options and 544 Move group options created over 250,000 combined Float–Move options. With the combined options available, another set of down selections was undertaken with a new set of criteria. In this case, the requirements used for this down selection were:

- Range at 15kts $>$ 11,500nm;
- Top speed $>$ 29.5kts.

This down select process reduced the number of combined Float–Move options from over 250,000 to 7179 options.

Combine Action to create Combined Float-Move-Infrastructure Options from Float–Move and Infrastructure Options

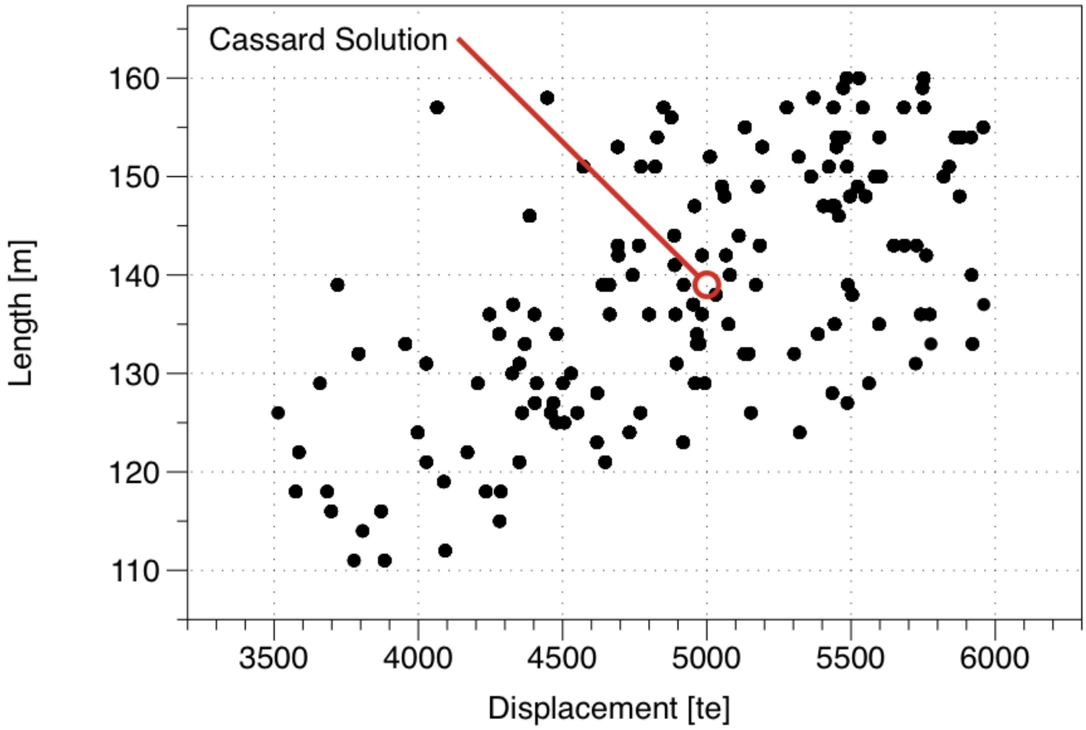
The final combination step in Figure 7.3, combined the down selected Infrastructure options with the remaining combined Float–Move options. By combining the 7179 Float–Move options with the 8 Infrastructure options over 76,000 combined Float–Move-Infrastructure options were generated. In this case, the requirements used for this down selection were:

- Unallocated Weight > 330te;
- Unallocated Volume > 2,160m^3;
- Cost < £150m.

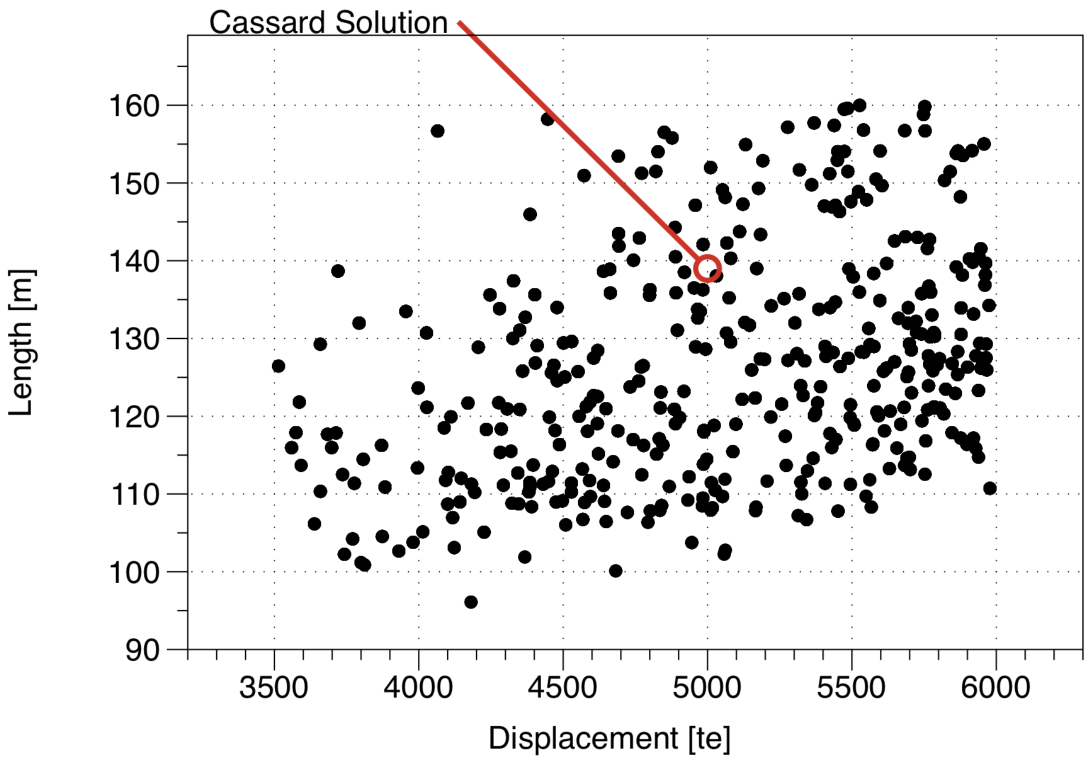
The unallocated weight and volume required in the design were estimated from the vessel's combat system and its associated variables. This down selection step resulted in excess of 76,000 initial combined Float–Move–Infrastructure options being reduced to 51,142 whole ship options that fulfil the requirements (including those associated with Operations/-Fight).

7.3.3 Presentation of Results

The whole ship options developed using the improved implementation can now be compared to the options developed with the exploratory implementation presented in Section 6.5. The simplest method of undertaking this comparison is to compare the performance and characteristics of the remaining 51,142 options with some 150 (Section 6.5.1) options generated by the exploratory implementation and presented in Section 6.5. Figures 7.4 to 7.7 provide comparisons between the options proposed by the improved implementation (Case III) and the exploratory implementation (Case I). Each of these figures contains both the original outputs of the exploratory implementation (Figures 7.4a to 7.7a) and the outputs of the improved implementation (Figures 7.4b to 7.7b). There is some variation in the solutions produced by the two implementations caused be the differing calculation methods used in the two implementations.

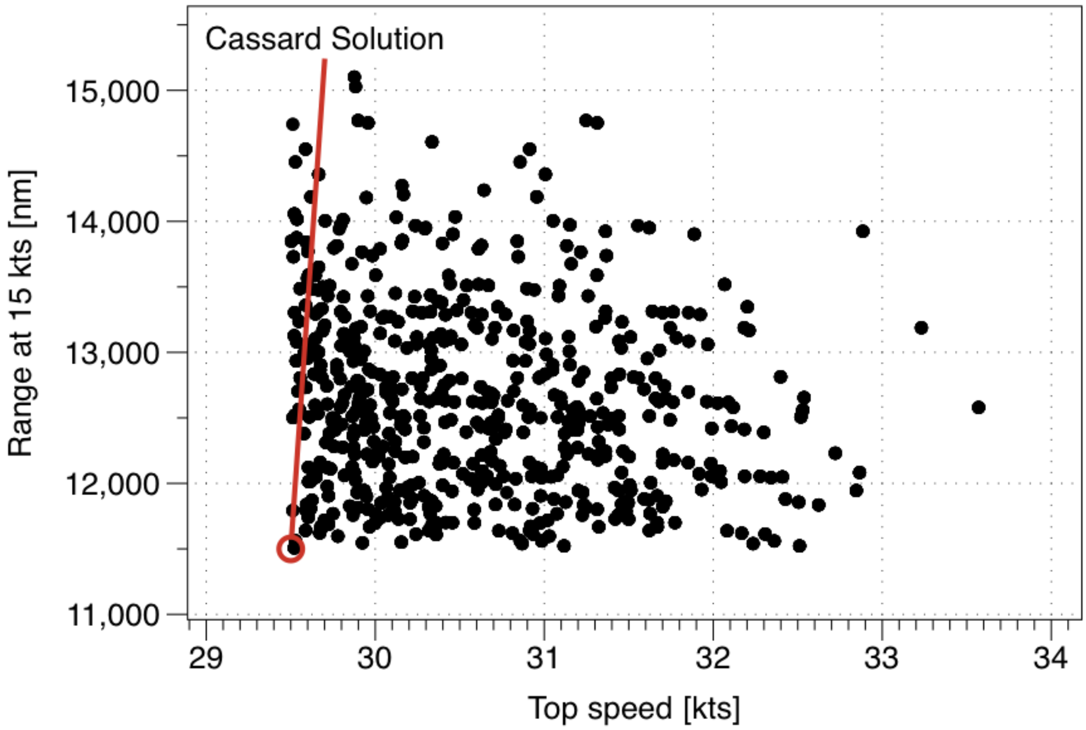


(a) Exploratory Implementation for Case I

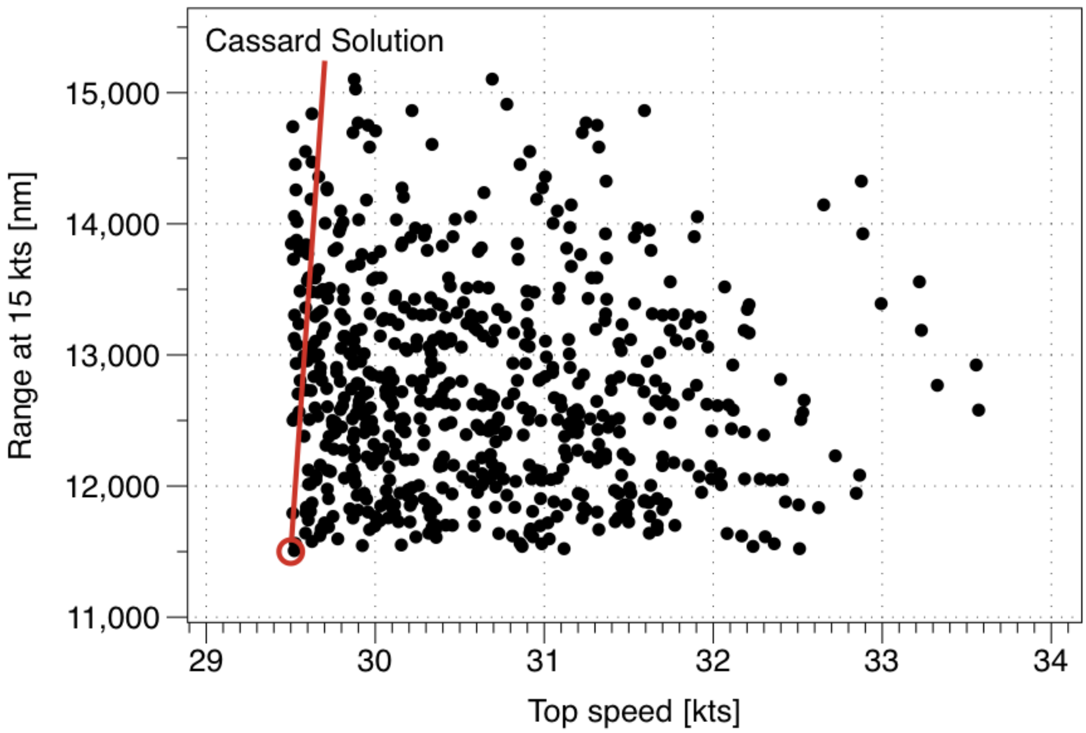


(b) Improved Implementation for Case III

Figure 7.4: Displacement and Length of Remaining Options

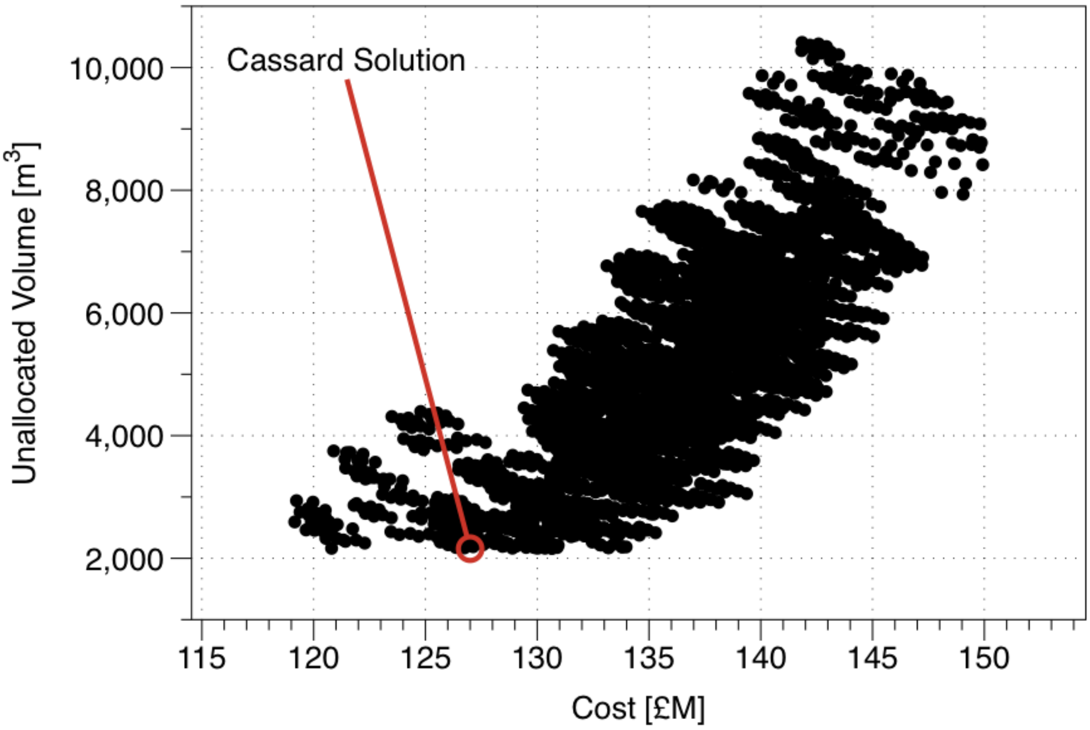


(a) Exploratory Implementation for Case I

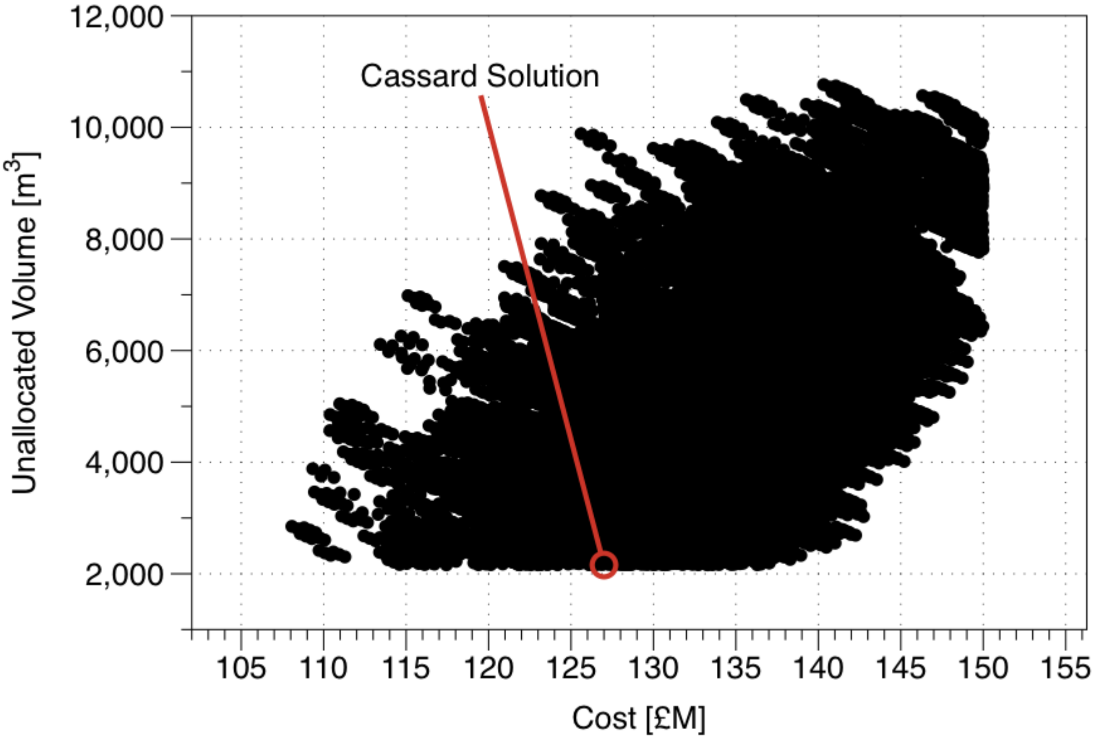


(b) Improved Implementation for Case III

Figure 7.5: Top Speed and Range of Remaining Options

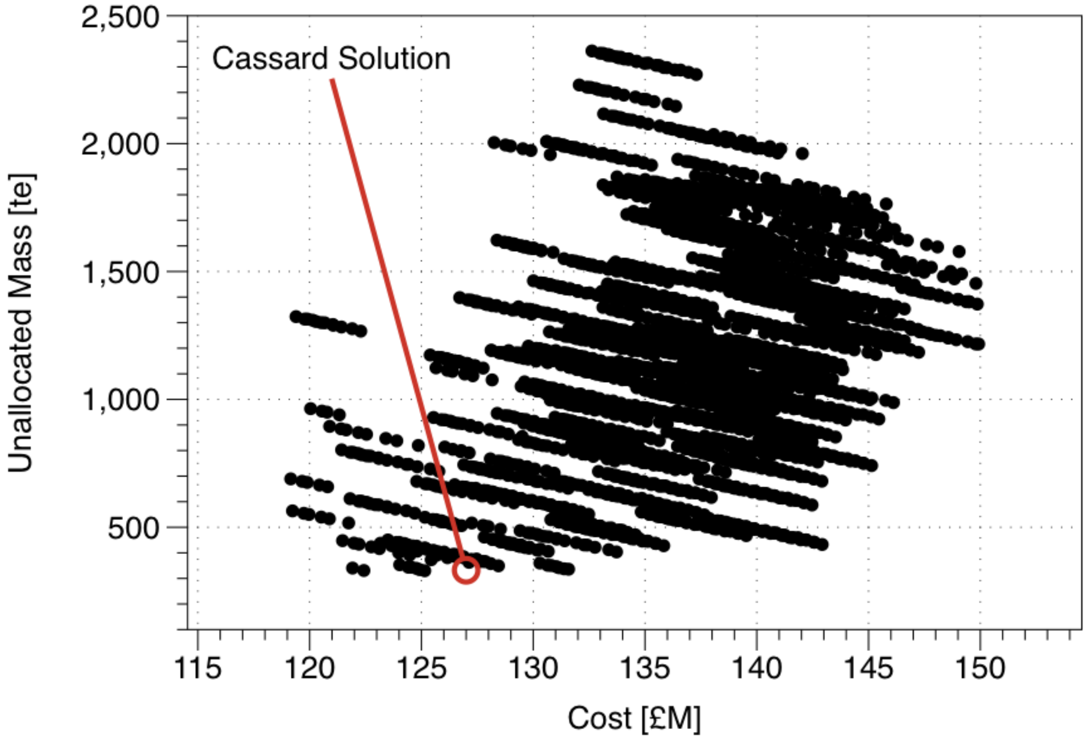


(a) Exploratory Implementation for Case I

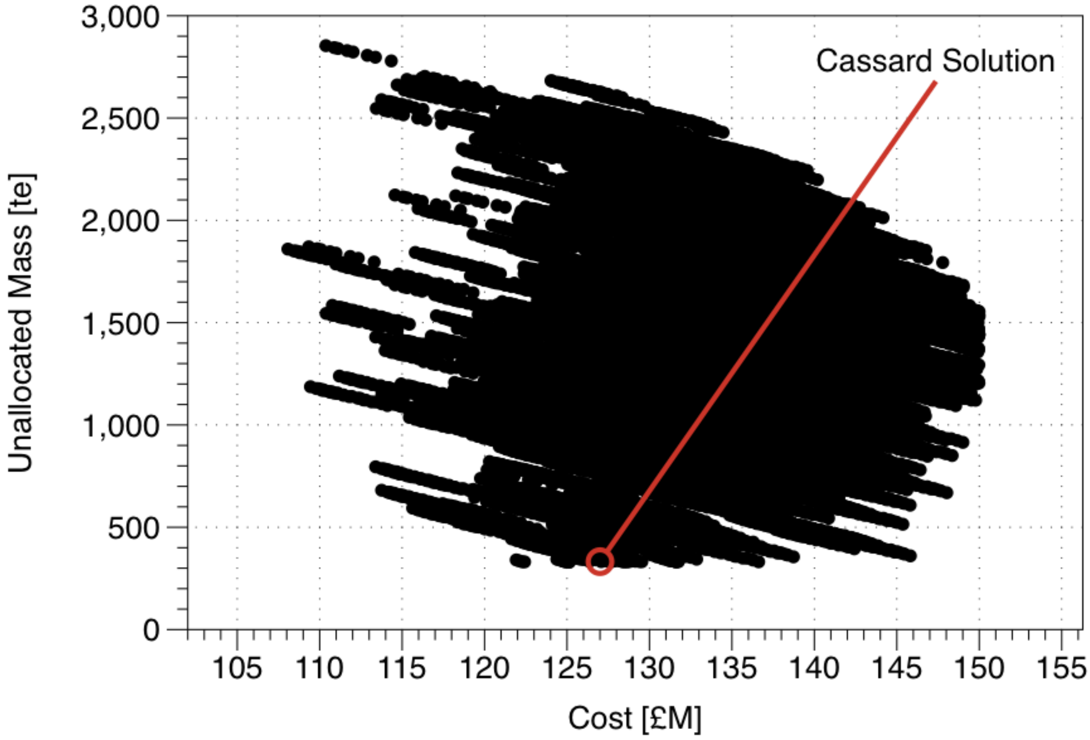


(b) Improved Implementation for Case III

Figure 7.6: Unallocated Volume vs. Cost of Remaining Options



(a) Exploratory Implementation for Case I



(b) Improved Implementation for Case III

Figure 7.7: Unallocated Weight vs. Cost of Remaining Options

7.3.4 Run Times

Section 6.7.2 identifies the speed of the exploratory implementation of the library method as a significant impediment to its practical utilisation. This section discusses the run times of the improved implementation for this case. The following data provides an indication of the duration of each step for the case described above. The code was run on a 2.4 GHz Apple MacBook Pro laptop with 2 GB of RAM. The total execution time was 34.35 seconds. Times for the individual actions are indicated in Figure 7.8. This total execution time compares very favourably with the exploratory implementation which required over two hours[2] to complete an equivalent task, namely, an increase in execution speed of 287 times.

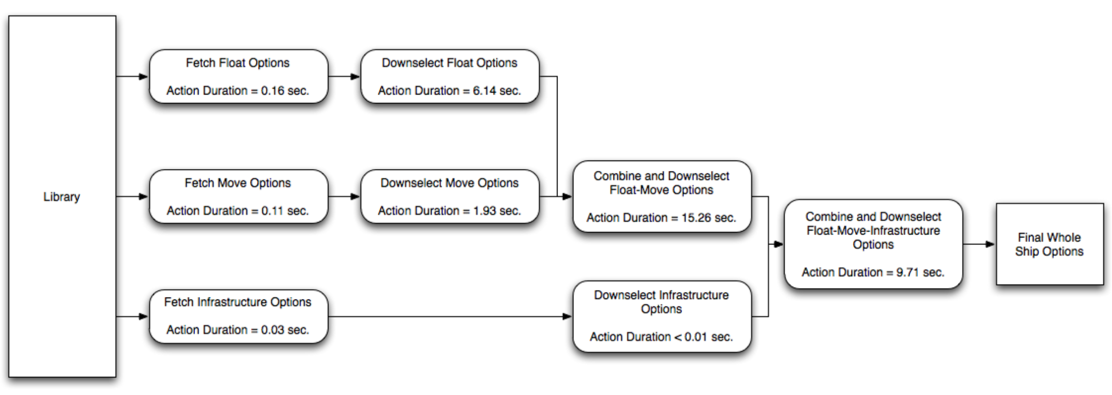


Figure 7.8: Total Duration for Different Actions for the Example Ship Concept Investigation (see Figure 7.3) with the Improved Implementation for Case III

The simple selection and combination steps underlying the process are amenable to being run in parallel. The options initially fetched from the library can be split across several equivalent operations required to perform the actions but which could be executed concurrently. Table 7.1 shows the variation in total run time for different library sizes and the number of concurrent actions. The second column, with two concurrent actions, indicates that the case presented in this section was run in parallel across two Central Processing Unit (CPU) cores in the test machine. In the one concurrent actions case, the program was limited to only running on a single CPU core.

Two cases are presented in Table 7.1, a simple case and a complex case. The simple case corresponds to the example case described earlier in this section (assessing a potential 42,090,048 possible combined options from an initial 1891 Float sub-options, 36 Infrastructure sub-options and 616 Move sub-options for Case III). The complex case is similar to the simple case but with four times the number of options in each of the Float, Move and Infrastructure sub-groups. This larger number of options was created by increasing the

[2]The exploratory implementation took two hours, fourteen minutes and fifty two seconds to complete an equivalent run (or 9,892 seconds).

granularity of the options, but not modifying the bounding values used by the methods generating the sub-options. This allowed the effect of a larger library to be explored without radically changing the proportion of options down selected in each step. Increasing the number of Float, Move and Infrastructure sub-options by four times leads to a 64 fold increase in total possible combined options (assessing a potential 2,693,763,072 possible combined options from an initial 7592 Float sub-options, 144 Infrastructure sub-options and 2464 Move sub-options)

Table 7.1: Total Run Times for the Illustrative Example of the Improved Implementation of the Library Method for Case III

	Concurrent Actions	
	1	2
Simple case	34.4 seconds	27.1 seconds
Complex case	545.6 seconds	464.9 seconds

7.4 Case IV: Exploring Alternative Hullforms

A prime objective of the proposed Library Based approach, which was not possible to demonstrate with the exploratory implementation presented in Chapter 6, was the ability to represent many alternate styles within the library. Section 7.2 introduced the improved implementation which employs a data structure allowing the representation of options via an arbitrary number of characteristics that can be defined by the designer. This allows the library to store and process options with a range of styles (Appendix F.1 provides further details of how this is achieved). The hullform selection problem that occurred as part of the LCS programme, described in Section 1.1.1, provides a suitable test case. Before the Library Based approach could be used to explore a set of options, the library had to be populated with data. In this case, Float, Move and Infrastructure sub-options were developed then stored in the library using the methods outlined in Section 7.4.1. Using this library a number of down selection and combination actions were used to explore the available options against the LCS requirements, these are described in Section 7.4.2. Discussion of the results and run time of the improved implementation are given in Sections 7.4.3 and 7.4.4.

7.4.1 Library Data Creation

The library data generation method used in this case differs from that described in Section 7.3.1 for Case III. In attempting to address consideration of different hullform styles there is a need to increase the accuracy and reliability of the assessment of performance attributes associated with the Float functional group, as this is critical in this example exploration process. Therefore, the Float sub-options were modelled in greater detail than the objects for the Move and Infrastructure sub-options. The key areas requiring modelling for the three functional groups are detailed within each sub-section (a), (b) and (c) below. The proposed solutions generated should be considered to be indicative of the type of solutions that could be employed as sub-options within a Library Based tool. The methods used to generate the sub-options are described in further detail in Appendix H.

a) Float Sub-Options

For the Float sub-options the following aspects were identified as being key to each Float sub-option:

- Geometry of the hullform;
- Resistance and propulsive power requirements;
- Weight and volume requirements of items within the Float functional group;
- Stability[3];
- Seakeeping performance.

Sub-options were developed for monohull, catamaran and trimaran hullform styles as shown in Figure 7.9. The same general procedure was applied to develop the Float sub-options. First, the geometry of the hullform was generated from a number of numerical inputs. Next, resistance estimates were undertaken using a thin ship theory resistance prediction tool [Lazauskas and Tuck 1997]. Sizing algorithms were then applied to obtain weight and volume requirements of items within the Float functional group. Finally, seakeeping performance in head seas was estimated using a simple strip theory analysis code [Smith 2008]. Further details of the method used to generate the Float sub-options for these hullforms can be found in Appendix H, Section H.2.1.

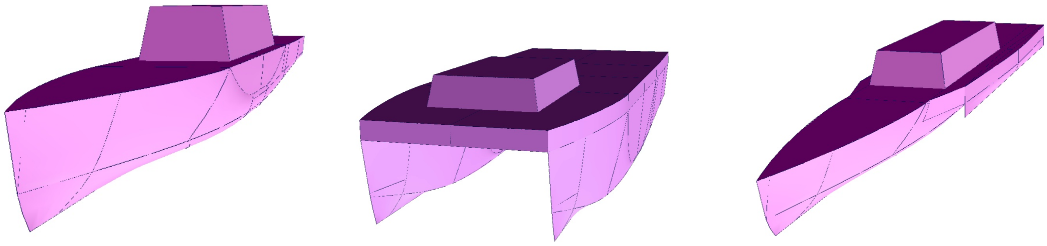
Using this method 3787 sub-options were developed, comprising: 1458 monohull sub-options; 1080 catamaran sub-options; and 1249 trimaran sub-options. Figure 7.10 gives an indication of the differing range of characteristics and performance for the Float sub-options selected for placement from within the library.

b) Move Sub-Options

The key performance metrics of interest for the Move sub-options are:

- Total power range of the propulsion system;

[3] For the Float sub-options presented here only the intact stability was examined. A similar process could be applied to damage stability calculation. See Appendix H, Section H.2.1 for further details.

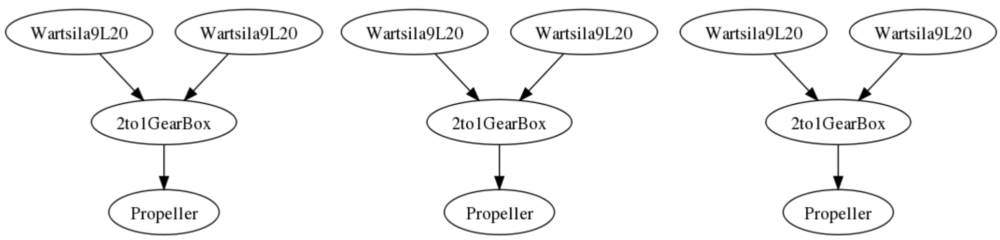


(a) Monohull (b) Catamaran (c) Trimaran

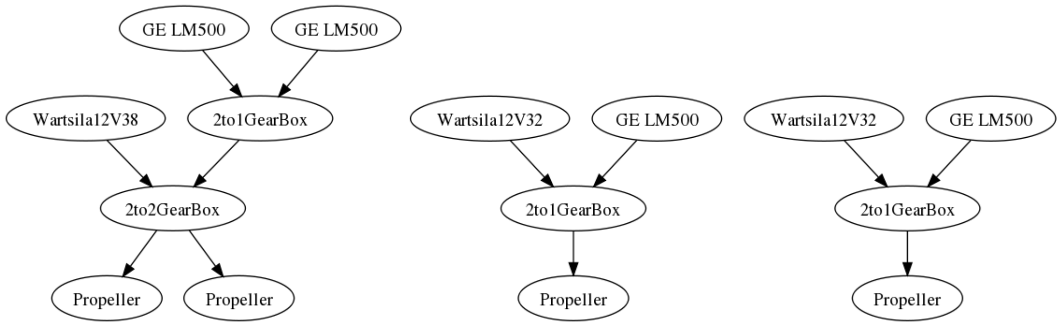
Figure 7.9: The Three Styles Explored for the Float Sub-Options in Case IV

- Fuel consumptions over the power range;
- Fuel capacity;
- Weight and volume requirements of items within the Move functional group.

Sub-options were developed for four styles of system topology (see Figure 7.11): single prime mover type; double prime mover type; mirrored single prime mover type; and mirrored single prime mover type. Figure 7.11, shows the items forming each simplified model of the mechanical propulsion system. The model represents a number of power sources (Wartsila diesel engines or Rolls-Royce/GE gas turbines) connected to one or more propellers, via a transmission system.



(a) Single Prime Move Type (b) Mirrored, Single Prime Move Type



(c) Double Prime Move Type (d) Mirrored, Double Prime Move Type

Figure 7.11: Example System Topologies for the Four Styles Explored for the Move Sub-Options

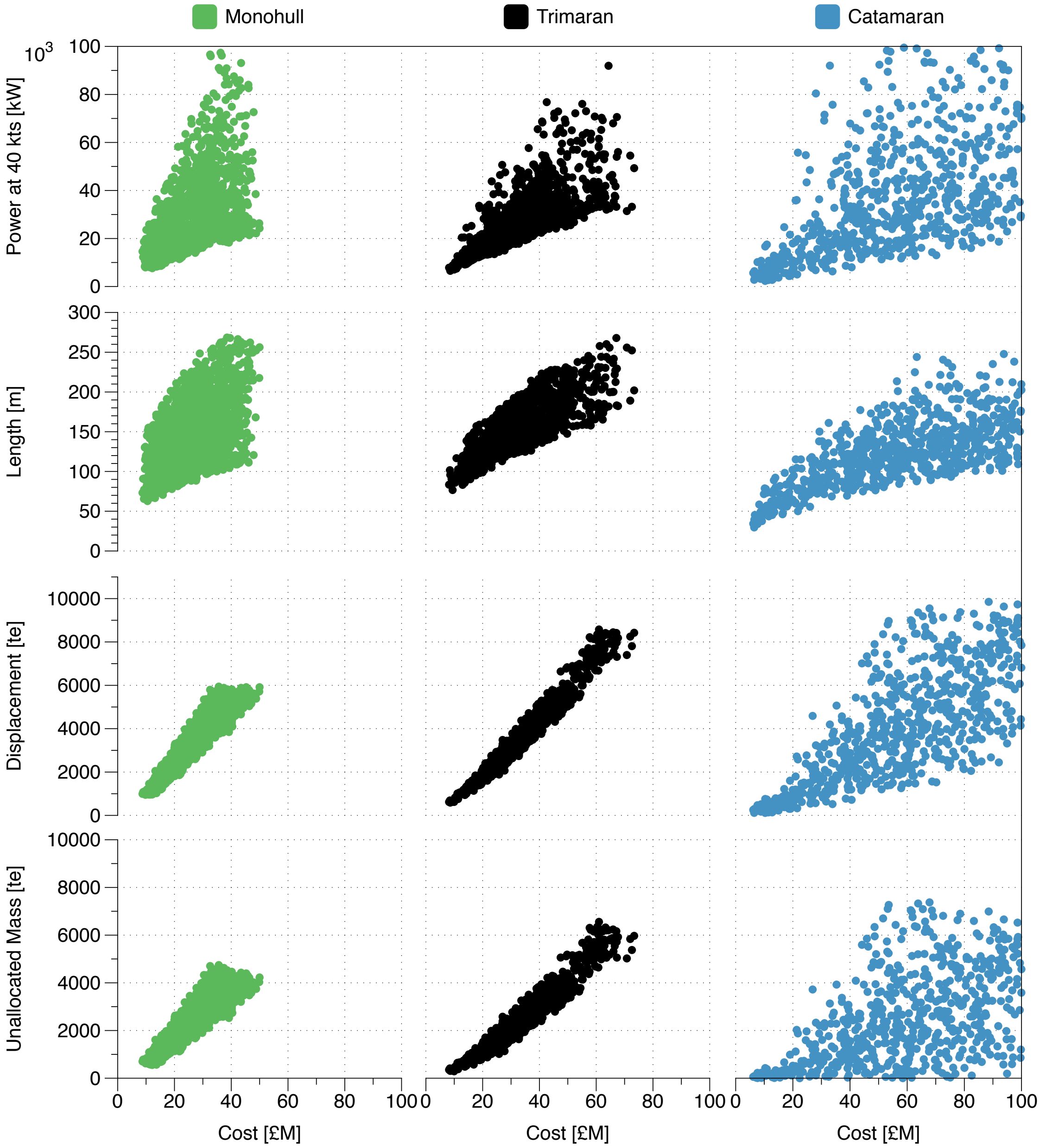


Figure 7.10: Power Required at 40 knots, Maximum Length, Total Displacement and Available Weight vs. Cost for the Three Float Sub-Options for Case IV of the Improved Implementation

The Move sub-options are generated using a simple tool developed by the candidate that allowed a large number of different machinery configurations to be produced and evaluated. This was necessary as the larger range of hullform styles would favour both different system topologies and different system components. The tool allowed the system to be described as a number of power sources (such as diesel engines or gas turbines) and power sinks (such as propellers) connected via a given transmission schema. System performance was then explored using an optimisation routine that found the most fuel efficient distribution of propulsor loading across the system over the system's operating range. Further details of the method used to generate the Move sub-options can be found in Appendix H, Section H.2.2. A total of 2560 different Move sub-options were generated, their performance is illustrated in Figure 7.12.

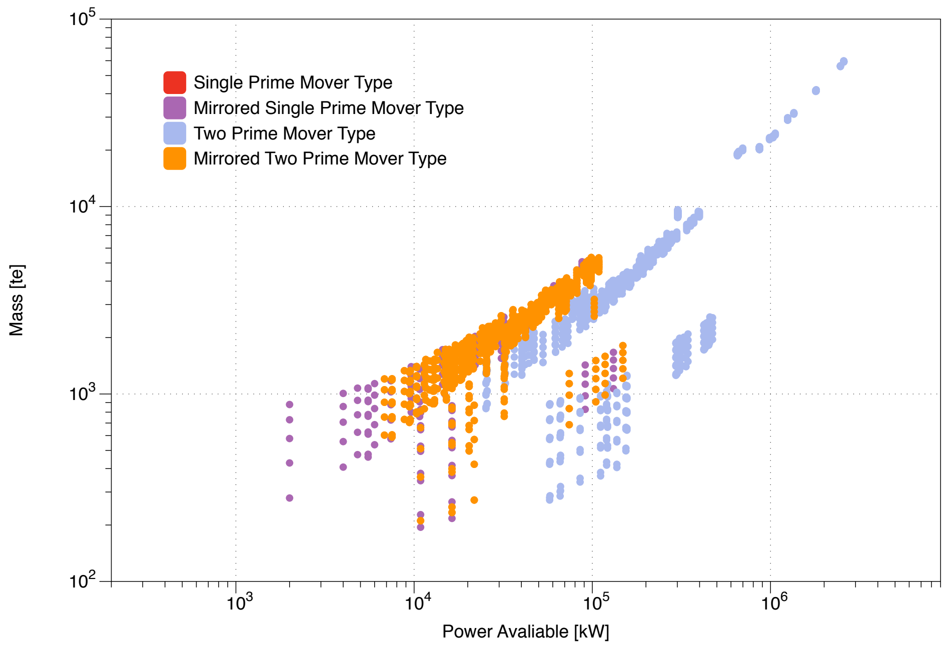


Figure 7.12: Delivered Power vs Weight for the Four Move Sub-Options for Case IV of the Improved Implementation

c) Infrastructure Sub-Options

The key metrics for the Infrastructure sub-options relate to the capabilities the vessel's Infrastructure services can provide to the other functional sub-options and to the 'payload' (Operation/Fight function). The following capabilities were deemed to be important:

- Crew availability;
- Power demanded for ship services and 'payload';
- Chilled water demanded for ship services and 'payload';

- Weight and volume requirements of items within the Infrastructure functional group.

Details of the method used to generate the Infrastructure sub-options can be found in Appendix H, Section H.2.3. A total of 583 different Infrastructure sub-options were generated, their performance is compared in Figure 7.13.

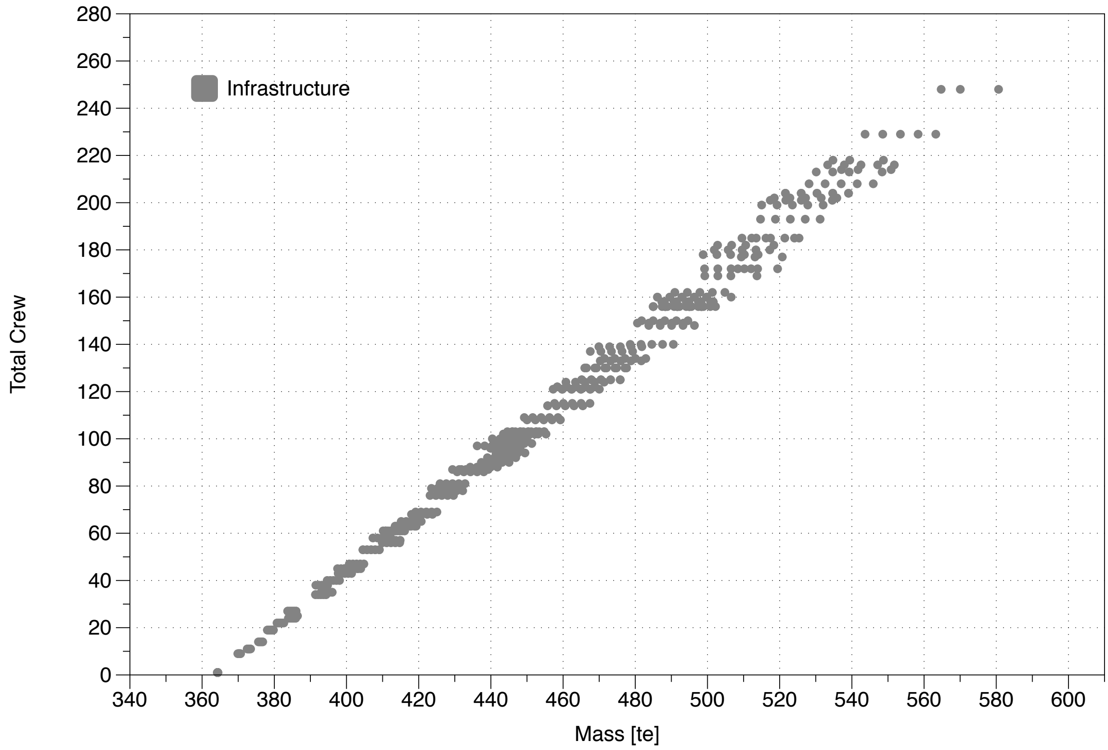


Figure 7.13: Total Crew vs. Weight for All Infrastructure Sub-Options for Case IV of the Improved Implementation

7.4.2 Down Selection and Combination Actions

The set of requirement defined at the start of the US Navy LCS design competition [US Navy 2003] has been used as a basis for the down selection of potential options. These requirements can be found in Section H.1 of Appendix H (on page 345) together with a demonstration of how they could relate to a specific library based tool which employs a Float, Move, Infrastructure and Operations (Fight) functional breakdown. From the analysis in Section H.1, of Appendix H, the requirements found in Table 7.2 were developed and used for the remainder of the presentation of this example.

Table 7.2: LCS Requirements used for Case IV Design Study

Function	Requirements			Notes
Float	Draught	$<$	6.10 m	
	RMS vertical velocity in SS4	$<$	1 m/s	a
	RMS pitch angle in SS4	$<$	1.5 deg	a
Infrastructure	Core Crew	$<$	50	
	Max Accommodation	$<$	75	
Combined Float–Move	Range	$>$	1000 nm at 40 kts	
	Range	$>$	3500 nm at 22 kts	
	Range	$>$	3500 nm at 16 kts	
	Range	$>$	500 nm at 6 kts	
	Maximum Speed	$\geq$	40 Knots	
Combined Float–Move–Infrastructure	Crew Available	$\geq$	Crew Required	
	Unallocated Weight	$\geq$	$330te$	b
	Unallocated Volume	$\geq$	$2050m^3$	c
	Total Cost (Excluding Payload)	$\leq$	£66M	d

[a] Seakeeping requirements based upon Section 7 & 8 of [Eriksen 2000].
[b] Developed using payload weight requirements from [McDonald et al. 2004]
[c] Developed using payload volume requirements from [McDonald et al. 2004]
[d] Developed using typical payload costs from [McDonald et al. 2004]. Original target cost (in $US) converted to match costing data available at UCL.

Several of these requirements were not explicitly defined in the original LCS requirements [US Navy 2003] but were developed using information derived from an earlier study by the candidate [McDonald et al. 2004]. Using the threshold requirements defined in Table 7.2 the following down selection and combination actions, described in the remainder of this section, were implemented:

- Action A — Float sub-options down selection;
- Action B — Move sub-options down selection;
- Action C — Infrastructure sub-options down selection;
- Action D — Float–Move options combination and down selection;
- Action E — Float–Move–Infrastructure options combination and down selection.

Action A — Float Sub-Options Down Selection

The six requirements used for the down selection of the initial library of 3787 Float sub-options are listed in Table 7.3. This table also contains the numbers of sub-options that were removed by each requirement. Applying the seven requirements from Table 7.3 resulted in the unacceptable Float sub-options being removed. This down selection resulted in 2964 Float sub-options remaining. Figure 7.14 illustrates these remaining sub-options showing the cost vs. displacement of the Float sub-options for the three hullform styles represented in the Library.

Table 7.3: Float Requirements Applied for Case IV Design Study

Requirement			Options Discarded
RMS vertical velocity in SS4[a]	<	1m/s	0
RMS pitch angle in SS4	<	1.5 deg	0
Displacement	>	330te	21
Draught	<	6.10 m	52
Unallocated Volume	>	2050m^3	41
Unallocated Weight	>	330te	188
Procurement Cost	<	£66M	542

[a]Note that as the RMS vertical velocity changes along the length of the ship the average RMS vertical velocity has been used in assessing this requirement.

Once these options were down selected it was possible to calculate performance metrics required for later actions (i.e. the propulsive power needed to achieve a speed of 40 knots—the required maximum speed, as prescribed in Table 7.2).

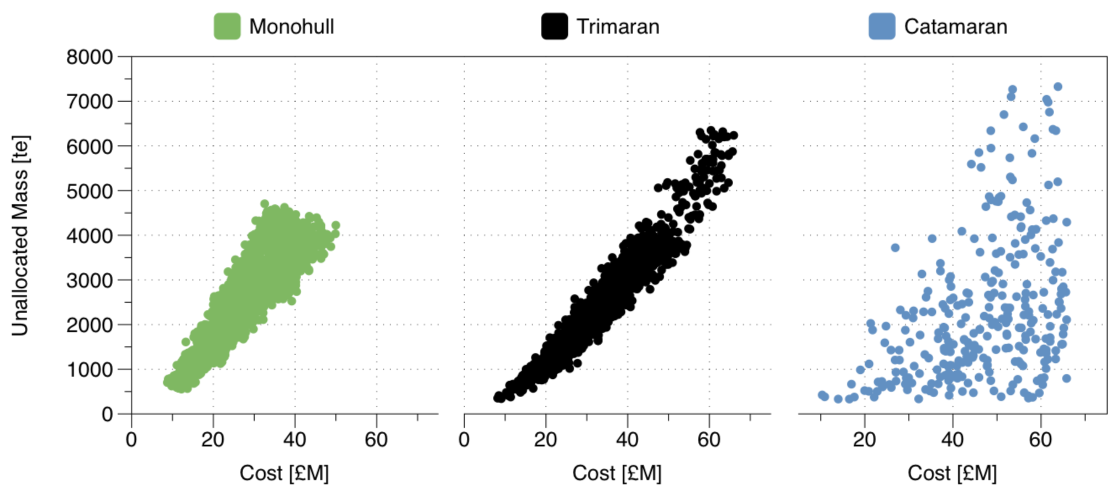


Figure 7.14: Unallocated Weight vs. Procurement Cost for Remaining Float Sub-Options for Case IV at the conclusion of Action A

The Float sub-options that remained at this point were passed to Action D to generate combined Float–Move options. However, it should be noted that these sub-options may be removed in the down selection that take place as part of Actions D and E.

Action B — Move Sub-Options Down Selection

The two requirements used for the down selection of the initial library of 2560 Move sub-options are listed in Table 7.4. This table also contains the numbers of sub-options removed by each requirement. Figure 7.15 shows the required propulsive power against the displacement of the acceptable Move sub-options. This down selection resulted in 585 Move sub-options remaining.

Table 7.4: Move Requirements Applied for Case IV Design Study

Requirement			Options Discarded
Available power	>	$7243kw$	170
Procurement Cost	<	£66M	1805

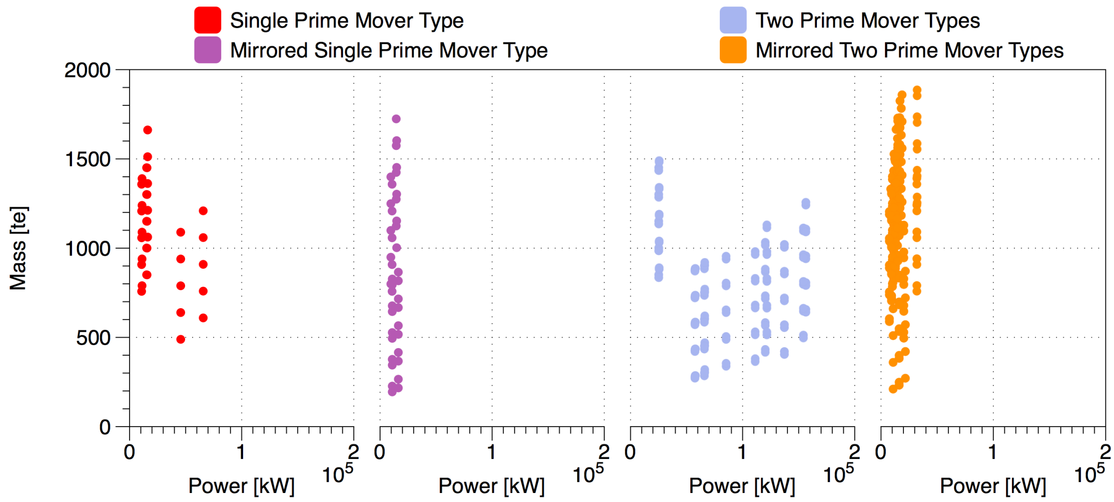


Figure 7.15: Available Propulsive Power vs. Weight for Remaining Move Sub-Options for Case IV at the conclusion of Action B

Action C — Infrastructure Sub-Options Down Selection

The two requirements used for the down selection of the initial library of 583 Infrastructure sub-options are listed in Table 7.5. This table also contains the numbers of sub-options removed by each requirement. Figure 7.16 shows the mass against the total crew provided by the acceptable Infrastructure sub-options. This down selection resulted in 205 Infrastructure sub-options remaining.

Table 7.5: Infrastructure Requirements Applied for Case IV Design Study

Requirement			Options Discarded
Max Crew	<	75	378
Procurement Cost	<	£66M	0

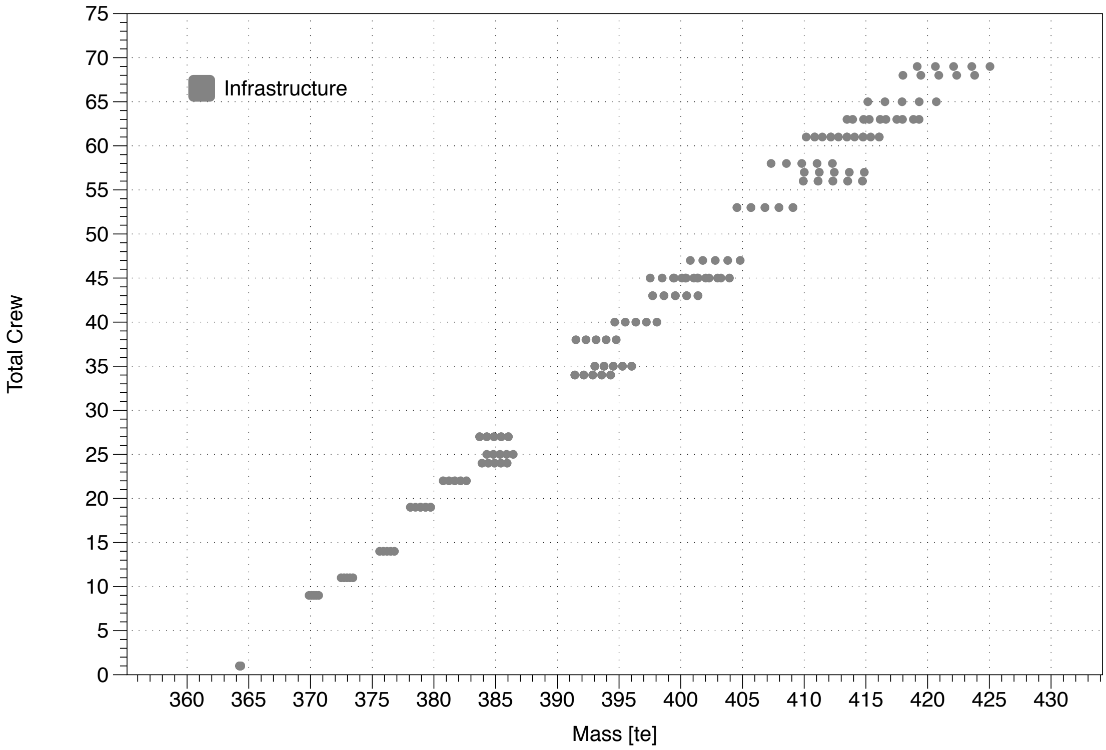


Figure 7.16: Available Propulsive Power vs. Weight for Remaining Infrastructure Sub-Options for Case IV at the conclusion of Action C

Action D — Float–Move Options Combine and Down Selection

Combining the 2964 Float sub-options and 585 Move sub-options gave a possible 1,733,940 combined Float-Move options. The eight requirements used for the down selection of these combined options are listed in Table 7.6. This table also contains the numbers of sub-options removed by each requirement. Besides these eight requirements, an additional check on styles was used to remove sub-option with incompatible styles. In this case, the Move sub-options with either of the two non-mirrored machinery styles (single prime mover and double prime mover) were defined as incompatible with the catamaran style Float sub-options. This allowed 51,450 possible combined options to be removed. Figure 7.17 shows the procurement cost of the combined Float-Move options against their unallocated weight. Figure 7.17a shows the remaining combined Float-Move options in terms of three hullform styles[4] while Figure 7.17b shows the four machinery styles[5]. This down selection resulted in 119,837 combined Float-Move options remaining.

Table 7.6: Float-Move Requirements Applied for Case IV Design Study

Requirement			Options Discarded
Unallocated Weight	>	$330te$	73,539
Unallocated Volume	>	$2050m^3$	0
Procurement Cost	<	£66M	897,993
Propulsive power required at 40 knots	<	Propulsive power available	366,291
Propulsive power required at 40 knots	<	Maximum power for a run time of 25 hours	160,118
Propulsive power required at 22 knots	<	Maximum power for a run time of 159 hours	35,458
Propulsive power required at 16 knots	<	Maximum power for a run time of 218 hours	29,254
Propulsive power required at 6 knots	<	Maximum power for a run time of 83 hours	0

Action E — Float–Move–Infrastructure Options Combine and Down Selection

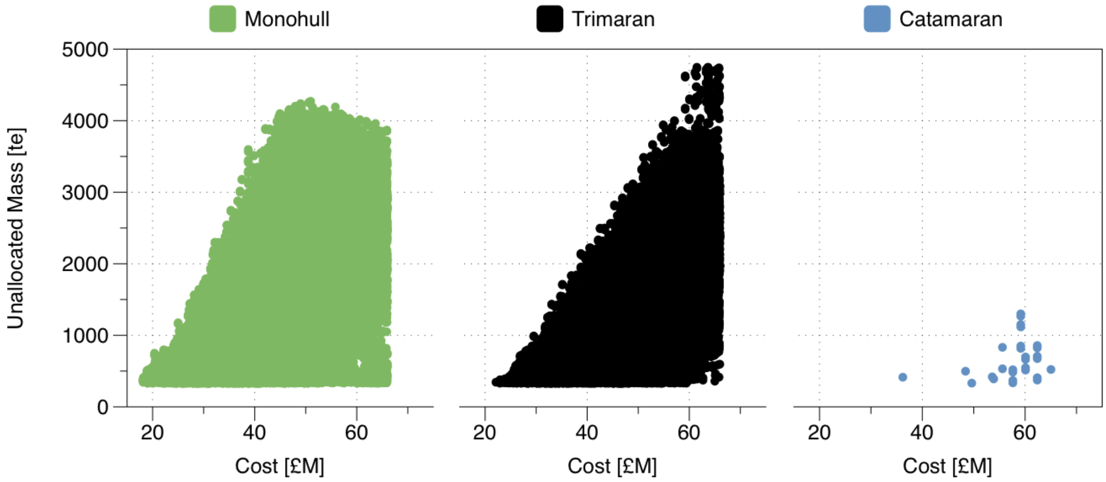
Combining the 119,837 combined Float-Move option from the previous step and 205 Infrastructure sub-options gave a possible 24,566,585 combined Float-Move-Infrastructure options. The four requirements used for the down selection of these new combined options are listed in Table 7.7. This table also contains the numbers of sub-options removed by each requirement. This down selection resulted in 25,195 combined Float-Move-Infrastructure options remaining. Figure 7.18 shows the procurement cost of the remaining combined options against their unallocated weight, with Sub-Figure 7.18a showing the hullform styles remaining and Sub-Figure 7.18b showing the machinery styles remaining.

Table 7.7: Float-Move-Infrastructure Requirements Applied for Case IV Design Study

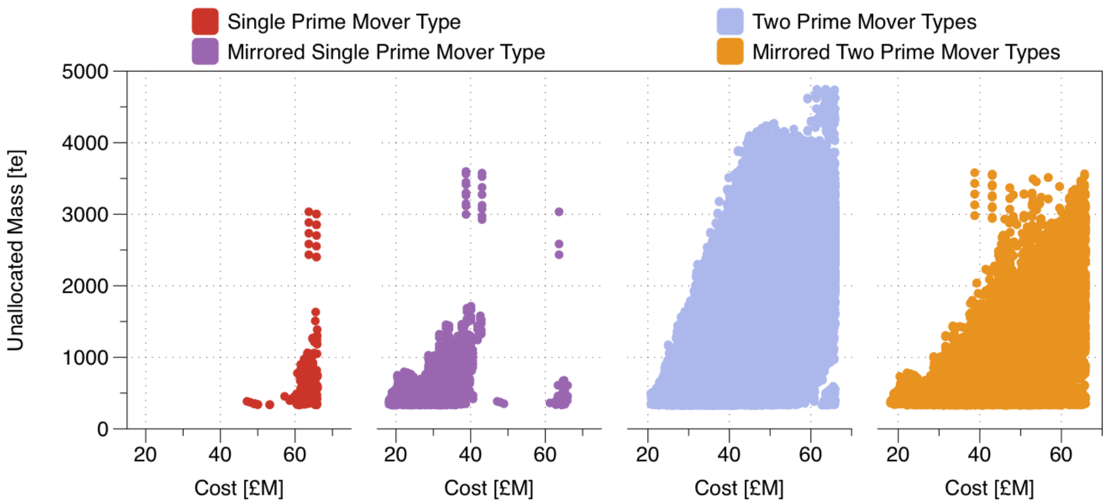
Requirement			Options Discarded
Unallocated Weight	>	$330te$	822,026
Unallocated Volume	>	$2050m^3$	1,374
Procurement Cost	<	£66M	281,490
Core Crew	<	50	23,436,500

[4] Which were 'monohull', 'catamaran' and 'trimaran'.

[5] Which were 'single prime mover type'; 'double prime mover type'; 'mirrored single prime mover type'; and 'mirrored single prime mover type'.

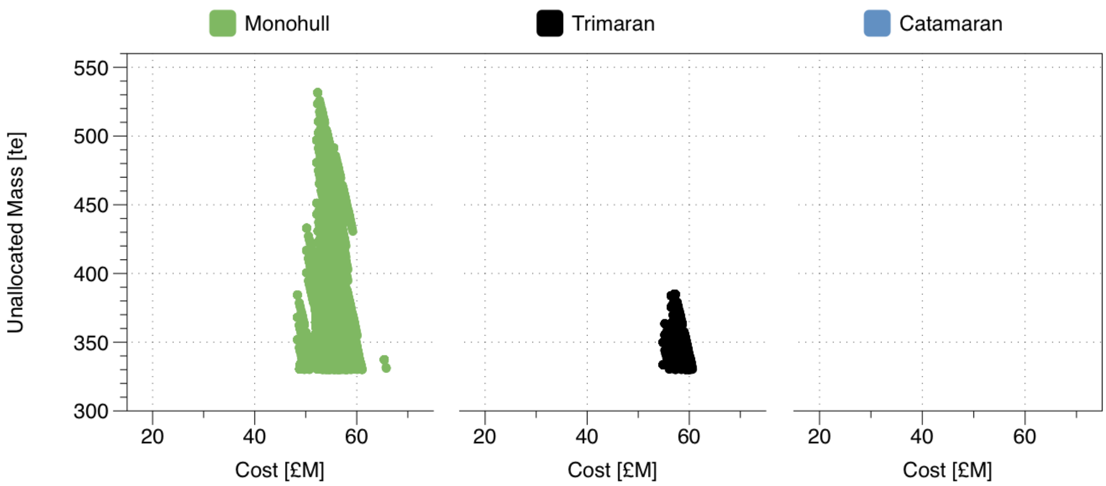


(a) Hullform Styles

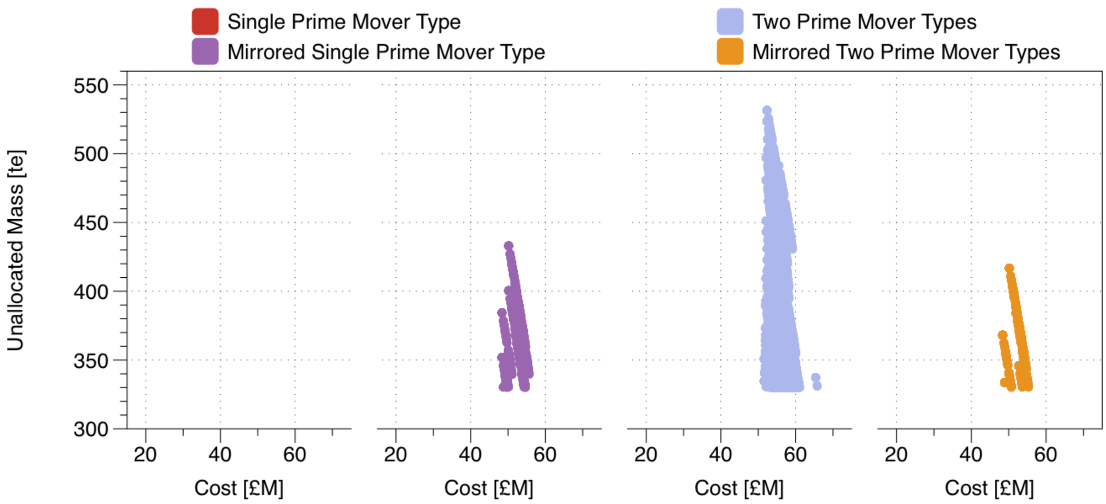


(b) Machinery Styles

Figure 7.17: Procurement Cost vs. Unallocated Weight for Remaining Combined Float-Move Options for Case IV at the conclusion of Action D



(a) Hullform Styles



(b) Machinery Styles

Figure 7.18: Procurement Cost vs. Unallocated Weight for Remaining Combined Float-Move-Infrastructure Options for Case IV at the conclusion of Action E

7.4.3 Presentation of Results

Figure 7.19 presents as histograms the number of options that remained for the styles present in the Library. From these plots it can clearly be seen that no catamaran style options remained but that either a monohull or trimaran style options could have provided an acceptable alternative for the specified requirements. Similarly, no machinery options with style that matched the single prime mover type remained. These results provided the designer with some guidance upon the styles of solution that it would have been advantageous to explore in the remainder of the design process.

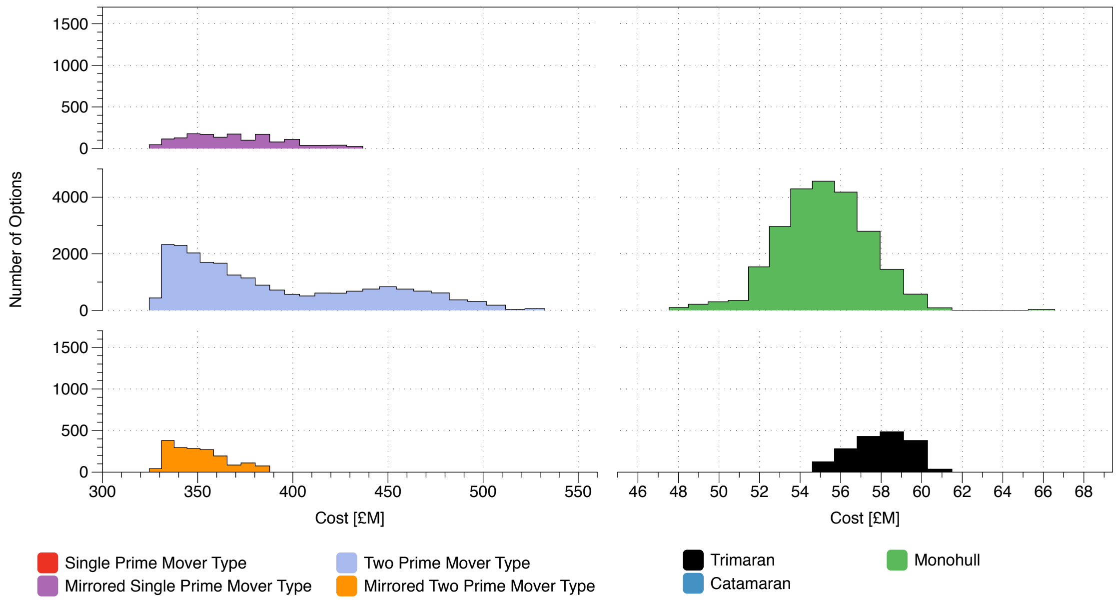


Figure 7.19: Distribution of Procurement Cost for Remaining Combined Float-Move-Infrastructure Options for Case IV at the conclusion of Action E

7.4.4 Run Times

An example of the run time for the improved implementation of the Library Based approach described in this chapter is given in Table 7.8. These times were obtained when running the implementation on a MacBook Pro 2.4 GHz Laptop with 2 GB of RAM.

7.5 Discussion of the Improved Implementation

The implementation of the proposed Library Based approach presented in this chapter is a considerable improvement upon the exploratory implementation presented in Chapter 6. The databased backed object-oriented programming approach that was adopted for its

Table 7.8: Run Time for the Library Based Approach for Case IV

	Action	Run Time (s)
A	Float Sub-Options Down Selection	38.11
B	Move Sub-Options Down Selection	7.75
C	Infrastructure Sub-Options Down Selection	2.98
D	Float–Move Options Combination and Down Selection	137.49
E	Float–Move–Infrastructure Options Combination and Down Selection	237.75

development has resulted in a tool that better supports the Library Based approach than the exploratory implementation.

Using the improved implementation, two example cases (described in Sections 7.3 and 7.4) have shown the enhanced speed and flexibility of the improved implementations compared to the exploratory implementation. Furthermore, Section 7.4 has shown that a Library Based approach is able to store information relating to options with different styles and then used this information in the down selection and exploration of potential options.

7.6 Conclusions on the Improved Implementation

The improve implementation, presented in this chapter, has achieved three key aims:

- Successfully demonstrate an increased execution speed relative to the exploratory implementation;
- Successfully demonstrate the ability to manage designs with different ship styles, through Case IV which feature the down selection of options with multiple hullform styles;
- Successfully demonstrate the ability to build up domain knowledge and implement practical performance prediction methods, thereby demonstrating the practical use of the proposed method.

The following chapter discusses the overall utility of the Library Based approach to ship design, given the outcomes of both developing and using the two implementations of the approach presented in this chapter and the preceding chapter.

8 Discussion

This thesis has investigated the task of hullform comparison and selection that occurs in the early stages of the ship design process. In the course of this investigation a gap in the range of design methods currently available to the designer was identified. To close this gap the thesis has proposed a Library Based approach for ship concept design, developed example implementations of the proposed approach and explored the application of the approach in elucidating the decisions taken early in the ship design process.

This research has been limited in scope to the examination of three hullform styles, to meet a set of naval ship requirements during the concept phase of the ship design process (Section 1.2). The limitation in scope is considered justified given the concept phase provides the greatest potential for exploring alternative ship options when compared to the remaining phases of the ship design process (Section 2.1). Furthermore, this exploration is necessary as alternative options, particularly different hullform styles, have been shown to offer considerable differences in performance and therefore potential advantages (Section 2.4).

The research has proposed a Library Based approach suitable for use in concept design, which can be applied to problems such as hullform selection. The proposed approach addresses issues not tackled by existing design approaches (Section 3.2). The Library Based approach allows the designer to better explore alternatives during concept design by facilitating a fast exploration of many possible options. The proposed approach employs combination and selection of a set of potential designs through examining a library of discrete options which have been divided into a number of sub-options based upon functional groups (Section 5.2). Furthermore, this rapid exploration of options can assist in the requirement elucidation process by encouraging a broader exploration of the design space (Section 2.3). This would then allow a designer to better explore the impact of requirements, and of satisficing those requirements (Section 2.3.4), across a large range of alternative options, however, links to other design approaches, better able to provide different forms of feedback, would also be advantageous.

The proposed approach offers advantages compared to other existing ship design approaches (Section 3.2 and 3.3). The Library Based approach is different to existing approaches as it recasts the design problem in terms of the combination and down selection of a wide range of options. This process provides information on which options are acceptable, given a set of requirements defined by the designer. Of the seven types of approaches to ship design discussed in Section 3.2 the Library Based approach is most similar to the Concept Exploration Based approach (Section 3.2.2) and Set Based approach (Section 3.2.7) both of which deal with a large diverse exploration to gain insight into the solution space. However, the Library Based approach differs from both of these as the library is intended to be built up by a design organisation over considerable time, then applied over a relatively short duration at the start of the early stage of the ship design process. Existing design methods are considered to be poorly suited in certain important aspects to this stage of the design process (Table 3.2 on page 96). One cause of this poor suitability is that existing ship design approaches require some style selection early in the design process (Section 3.3). In contrast, the Library Based approach is intended to help guide and inform the designer engaging in this style selection activity. Consequently, it is well suited for use during the preparation stage outlined by Pawling (see Section 3.3, specifically Figure 3.8) that forms a key part of the 'genesis step' that occurs at the start of the design process (Section 4.3.1).

The Library Based approach is intended to facilitate working across a design team or organisation. Thus it is intended to encourage the members of the design team to externalise design information, a process that March suggests as desirable as part of his PDI model of design (Section 4.3.1). This supports the development of structured knowledge on both designing and the ship design process. The Library Based approach is considered to have distinct advantages as it allows storage of information on both the form and function of options that lie in the solution space. This stored information could enable a mapping between form and function, previously recognised as a complex issue (Section 2.2.1). In turn, this could allow the designer to build a domain theory that links the solution space and performance space (Section 4.2.1). Such a domain theory has the potential to help support designer reasoning, as highlighted by Kroes (Section 4.2.1, specifically page 102). However, the large degree of complexity of both a ship design and the ship design process is recognised as arising from the significant issues that occur at the outset of the ship design process (Section 2.2). The Library Based approach is unable to directly tackle the complexity of ship design, however it may lead to some reduction in the difficulties that arise in early ship design by reducing the cost (in time, money and other resources) of widely exploring options early in the design process. This could then lead to a reduced likelihood of a superior alternative being discovered later in the design process or being missed altogether. It could even lead to improvements in tackling the wicked nature of the requirement elucidation process (Section 2.3.3).

During the course of the research, two example implementations of the Library Based approach were developed by the candidate (Chapter 6 and 7). Chapter 7 describes an implementation of the Library Based approach which gives a framework for addressing topologically different solutions, not readily provided by other approaches surveyed (Chapter 3). It also shows how a Library Based approach can provide the designer with information to aid their decision making process. Chapter 7 also demonstrates that the Library Based approach could be implemented in a manner that is agnostic to major design style choices. In addition, the candidate explored the application of both databases and object oriented programming in developing the implementations (Section 4.4.1) to support the rapid exploration of options. Further increases in the speed of producing options in future implementations of the approach may be possible but this may require the adoption of different data management techniques. Any such increase in operational speed would further improve the utility of the approach.

The remainder of this chapter contains further discussions on the Library Based approach divided into the following five topics:

- How the approach compares to the needs of the ship concept design tool;
- The impact of the approach on wider design, beyond the Library Based approach itself;
- A review of the process adopted in the approach;
- Technical issues that have arisen in the current implementations of the approach;
- Other issues that have emerged during the development and use of the approach.

These topics are discussed in Sections 8.1 to 8.5. After discussing these topics the original scope, presented in Chapter 1, is reviewed in Section 8.6.

8.1 Comparing the Library Based Approach to the Needs of a Ship Concept Design Tool

The conclusions of Section 3.4 (on page 94) presented Andrews' [2003b] and Betts' [2000] separate lists of features necessary for a design approach to fully support the ship design process. Now that the Library Based approach has been demonstrated, the capabilities of the approach can be compared against Andrews' and Betts' lists of features. The results of this comparison can be found in Tables 8.1 and 8.2 (on pages 196 and 197 respectively). Each table provides details of how the proposed Library Based approach matches Andrews' or Betts' lists of features. It can be seen that the proposed Library Based design system provides many of the features they suggest. However, in certain areas further developments are desirable, these areas are detailed in the remainder of this chapter. The extreme right hand column in both Table 8.1 and 8.2 links Andrews' and Betts' lists to the detailed discussion in Sections 8.2 to 8.5 of this chapter.

Table 8.1: Comparison of Library Based Approach with Betts' [2000] List of Features Necessary to Fully Support the Ship Design Process

Necessary Features	Capability of a Library Based Approach	Sections
Utilise data for assessment of performance, risk and through life cost;	With appropriate data in a library the approach can be used to rapidly assess the performance, risk and through life cost;	8.3.1
Usable by knowledgeable design team;	The current user interface of the Library Based approach is not simple enough for use by a knowledgeable design team;	8.5.1; 8.5.2
Deal comparably with conventional and unconventional ship concepts;	The approach has been demonstrated to work for a case involving conventional and unconventional naval ship concepts;	8.6
Provide reasonable (preliminary) solutions;	The approach provides an indication of potential options in the form of a number of preliminary solutions;	
Assist communications with design team and all stakeholders, especially those evolving the operational requirement.	The rapid speed of operation allows the designer to quickly respond to queries aiding communication with the requirement owner and specialist users.	8.5.2; 8.2.2

Table 8.2: Comparison of Library Based Approach with Andrews' [2003b] List of Features Necessary to Fully Support the Ship Design Process

Necessary Features	Capability of a Library Based Approach	Sections
Believable solutions, meaning ones that are both technically balanced and descriptive;	The approach provides an indication of potential options in the form of a number of preliminary solutions;	8.3.1
Coherent solutions, meaning that the dialogue with the customer should be more than merely a focus on numerical measures of performance and cost, and should include visual representation;	Integrating the method presented here with a visual representation could allows a dialogue with the customer beyond simple numerical measures of performance and cost;	8.2.3; 8.5.2
Open methods, in that they are responsive to the issues that matter to the customer or capable of being elucidated from the customer or user teams;	The rapid manner in which the options are down selected is highly amenable to alteration, allowing the designer to respond quickly to issues generated by the customer. Coupling this method with an appropriate visualisation and design tool should allow rapid exploration of options, improving the design team's responsiveness to customer queries and hence achieve Requirements Elucidation's aims [Andrews 2003b];	8.2.3; 8.4.3; 8.5.2; 8.2.2
Revelatory, so likely design drivers are identified early in the design process to aid effective design exploration;	The proposed method and tool can be used to quickly identify numerical design drivers early in the design process. But to realise its full potential, as an aid to effective design exploration, links to an approach that considers configuration need to be developed further and the performance improved for larger library sizes;	8.3.3; 8.2.3; 8.5.2; 8.2.2
Creative, in that options are not closed down by the design method and tool but rather alternatives are fostered.	Compared to other ship design methods, by allowing the designer to postpone the selection of hullform style, this method allows options to remain open until later in the design process, hence fostering the development of alternatives.	8.2.1; 8.3.2

8.2 Impact on Wider Design

In examining the impact of the proposed approach on wider design, one of Betts' needs (see Table 8.1) and three of Andrews' needs (see Table 8.2) are seen to be satisfied by the Library Based approaches capabilities, namely Andrews' needs for creativity, open methods and coherent solutions together with Betts' need to assist communication.

In response to Andrews' need for creativity, the Library Based approach allows options to remain open longer by postponing the selection of style. This can be illustrated by considering the application of the proposed approach in concert with the Set Based Design approach discussed in Section 3.2.7. Specifically, there is the potential to adopt a Library Based approach to assist in intra-group communication and decision making within a team conducting a design using a Set Based Design approach. This issue is explored in Section 8.2.1.

In response to Betts' need to assist communication and Andrews' needs for open methods and to be revelatory, the capabilities of the Library Based approach to provide insight and explanation to the designer are examined in Section 8.2.2. The current implementation is found to fall short of what a designer may desire. However, a potential route for further development is identified, examining the common characteristics of the solutions that are down selected or removed, which may allow the Library Based approach to be extended to expose the relationships or drivers within designs.

In response to Andrews' need for open methods and coherent solutions, the proposed approach allows rapid exploration of the design requirements in an open manner to develop coherent solutions. However, significant advantages would arise from integrating the approach presented here with some visual representation of the design. It is suggested that this would better foster the dialogue between the designer and customer by extending it beyond the simple numerical measures currently stored within the library, such as performance and cost. This would allow the designer to present the customer with an integrated configuration based design, while simultaneously allowing the rapid exploration of multiple options (such as radically different hullform styles) using the Library Base approach. This issue is further explored in Section 8.2.3 which discusses alternatives for combining the Library Based and Design Building Block approaches.

8.2.1 Utility in Set Based Design

As stated above, there are potentially promising overlaps between the Library Based design approach presented in this thesis and the Set Based Design approach discussed in Section 3.2.7. Compared to other ship design methods the Library Based approach allows options to remain open until later in the design process as the designer can postpone the selection of style. This fosters the development of alternatives that may have previously been discarded and can therefore be seen to encourage Set Based Design (as outlined by [Parsons et al. 1999; Singer 2003]).

In addition, while Set Based Design provides a general strategy suitable for use by large design teams composed of multiple specialists, it is often difficult for the project leader to successfully manage the project if a large number of topologically differing design options are being considered; a role where a Library Based design tool could readily provide assistance. Furthermore, if a Library Based tool were accessible to all team members engaged in a Set Based Design approach then it would allow the design team to rapidly explore alternative options and, therefore, be better informed of promising options.

8.2.2 Providing Insight and Explanation to the Designer

The Library Based approach presented in this thesis is seen to provide a powerful basis for a tool intended to assist the designer with exploring options. However, designers are also interested in exploring and elucidating the design requirements (see Section 2.3.2), specifically the interaction of a requirement with other requirements. The implementations of the Library Based approach presented in Chapter 6 and 7 demonstrated a system able to explore options. Furthermore, by varying the requirements and payload entered into the tool the effect of these inputs upon the solution space could be explored. However, the Library Based approach, as presented in this thesis, is unable to provide a designer with any direct feedback of the interrelationships between various requirements. Specifically, the tool is unable to provide direct information as to how specific requirements may drive specific design options; an activity which can be termed as the exposure of relationships or drivers.

The work presented in this thesis did not explore the ability of the Library Based approach with regards to revealing or exposing relationships or drivers within a design. The implementations of the Library Based approach, presented in Chapter 6 and 7, indicate there are considerable barriers to undertaking such an examination: for reasons of memory efficiency, both implementations discarded options which failed to meet the requirements, thus removing potentially useful information as to why options have failed; there are also inherent limitations' in the implementations current data storage systems with respect to their ability to rapidly identify similar solutions. Additionally, exposing relationships or drivers was viewed as beyond the scope of the research, as outlined in Section 1.2. However, there would be considerable advantages to developing mechanisms able to allow such an exploration in future version of the Library Based approach and implementations of the approach.

The route towards implementing some means of exposure of relationships or drivers is not obvious, thus it has not been possible at the conclusion of this research to identify a simple solution to this. The most promising alternative may be to undertake some assessment of the logic or reasons why certain types of solutions are removed during the down selection process. There may be merit in employing a clustering[1] approach to identify similar options (i.e. options with the same style and similar characteristics) and assess if certain requirements caused these options to be down selected or rejected. However, this is beyond the capabilities of the current Library Based implementations. If other implementation employing the Library Based approach were developed, then there would be considerable merit in further exploring these issues. If developed, this enhanced capability is likely to be of interest to the designer as it may then provide significant insights into the interaction of requirements with other requirements while also exposing the reasons why certain options are or are not acceptable.

8.2.3 Integration with other Design Methods

The Library Based design approach demonstrated in this research does not address all that is likely to be required even in the early stages of the ship design process. It is intended to be employed in concert within other design methods or approaches. This has been illustrated by considering how the system could be employed in conjunction with the fully integrated ship synthesis approach presented within [Andrews 1986][2]. Figure 3.2 (on page 83) reproduces Andrews' representation of the design process [Andrews 1986]. It is possible to show the proposed Library Based design system's place within Andrews' design process and this adaptation is shown in Figure 8.1. Within Andrews' process the conscious primary generator can be viewed as a kernel about which the designer tackles the style issue, enabling an initial design to be created. It is envisaged that a Library Based design system would act as a supportive mechanism to Andrews' synthesis approach and this would then help the designer to determine an appropriate primary generator (within the synthesis process shown by Andrews). In this way the Library Based tool would act as a bridge between the task directed input, user input, the design process constraints and the designer's idiosyncratic stamp shown in Figure 8.1.

Such a supportive role by the proposed Library Based approach would only be possible if appropriate mechanisms providing clear feedback on the impact of design decisions were possible. These mechanisms could take a number of forms:

- Procedural requirements that ensure a designer (or concept design team) recognise they are operating in a manner suggested by Figure 8.1;

[1] Clustering is a method of unsupervised learning that refers to the assignment of a set of items into subsets (called clusters) so that items in the same cluster are similar (in some sense). One clustering technique—hierarchical clustering—seems applicable to the problem of identifying links between options and requirements. It relies upon creating a hierarchy of clusters, represented by a tree structure that partitions the options into smaller clusters [Kaufman and Rousseeuw 2005]. Exploring how the requirements interact with these clusters may be one way to begin exploring the nature of the manner in which requirements drive solutions.

[2] Andrews' fully integrated ship synthesis approach sees this approach to synthesis as a more challenging problem since it clearly recognises the role of a designer's idiosyncratic stamp, a key aspect of the design process, as shown in [Lawson 2006] and [Daley 1982].

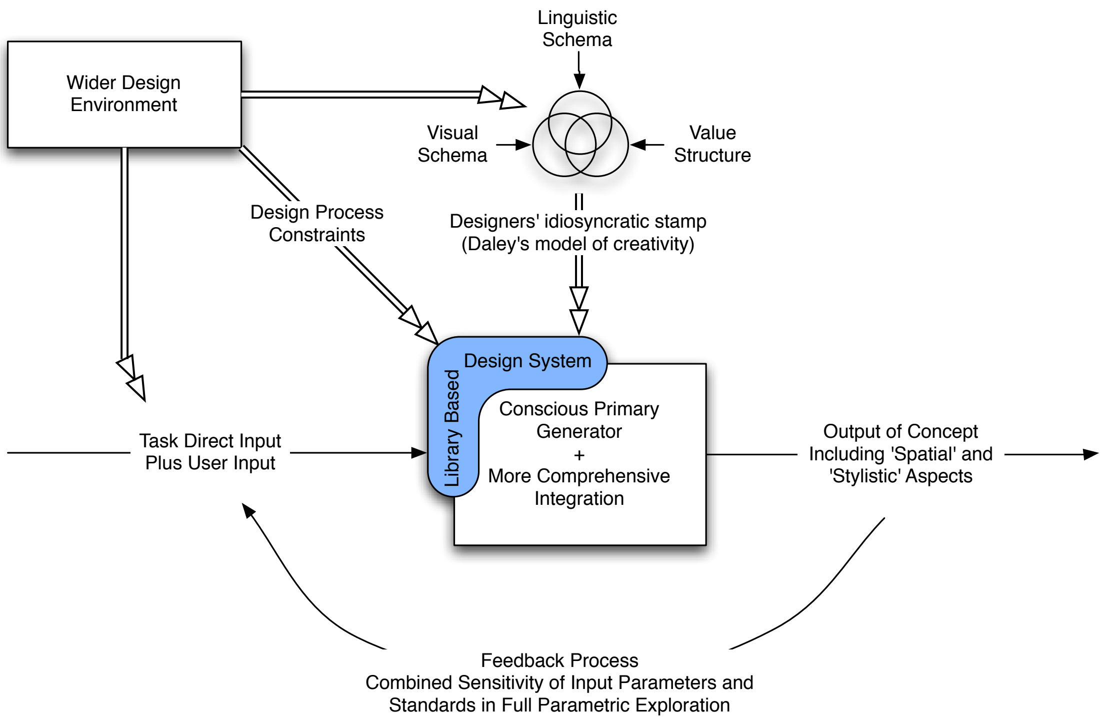


Figure 8.1: Adaptation of Andrews' 'Holistic' Approach to a Fully Integrated Ship Synthesis Showing the Role of the Library Based Approach, developed from [Andrews 1986]

- Constraints imposed on the project by design practice, that ensure a requirement elucidation process is adopted (as opposed to the sequential (requirement then design) Requirements Engineering process that frequently occurs in current naval ship procurement [Andrews 2003b]);
- Inserting specific features into the design approach that would then provide immediate feedback to the designer.

The Library Based approach should be able to offer the designer information on the impact of requirements upon the available options by the mechanisms above. The integration of the proposed methods with a configuration based design tool is discussed further in [Andrews et al. 2010] which is included in this thesis as Appendix I.

8.3 Review of Process

Examining the process that the proposed approach adopts, it is apparent that one of Betts' and three of Andrews' needs (see Table 8.1 and 8.2) can be directly supported via the Library Based approach. These are: Betts' need to utilise data to assess performance, risk and cost; and Andrews' needs to develop believable solutions, to be revelatory and to be creative. By enabling a flexible application of requirements specified by the designer, against an appropriate library of options, these needs could be satisfied. This has been demonstrated through two separate implementations, detailed in Chapters 6 and 7. These implementations have been tested via a number of example cases, one of which compared the outputs of the tool to an existing ship design project. While these cases showed that the implementation could be used to explore the available options (including options with different styles), they also revealed some issues that have arisen from using the specific prototype design tool presented. These issues are discussed in Sections 8.3.1, 8.3.2 and 8.3.3.

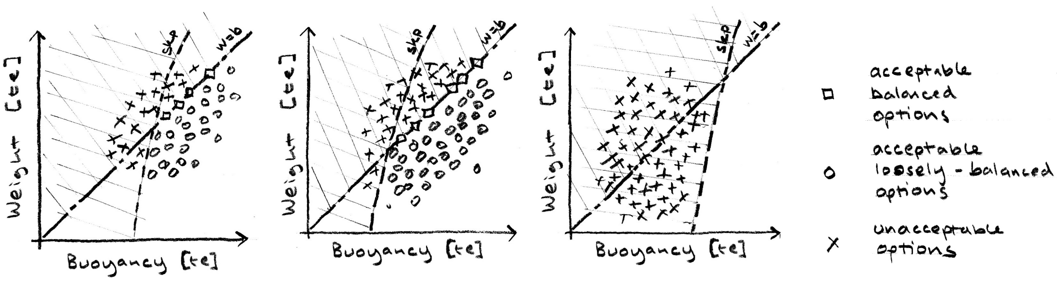
8.3.1 Requirements and Down Selections in the Proposed Approach

Section 7.4 highlighted how requirements for a real project can be used to filter the available options, thereby reducing the total number of options that need to be considered. Other techniques could also be applied to reorganise the order of the performance prediction and down selection sequence, allowing a reduction in the number of options that need to be examined (possible techniques are discussed in Appendix F, Section F.1.4). These techniques would help reduce the number of options considered and could therefore be used to speed up the process of using a given tool implementing the Library Based approach.

One of these techniques is seen to offer significant advantages in reducing the number of combinations and down selections that need to be performed. The proposed Library Based approach decomposes each option into a number of sub-options which are later combined (see Figure 5.9). The implementations presented in Chapters 6 and 7 are based upon a tree of sequential combination and down selection actions, as shown in Figures 6.2. However, these sequential actions fail to make as great a use of all available information on the remaining options as is possible, particularly with regards to the interrelationships between the options and the applicable requirements. For example, the cost requirement was applied at each down selection step in Case V (from Section 7.4) to successfully remove sub-options or combined options. However, as each sub-option's cost was known at the outset of the process, this meant the library contained sufficient information to identify combinations of sub-options that would not meet this requirement. A possible area of future work is therefore to explore mechanisms that would allow requirements to be mapped backward up the hierarchy of combination actions, thereby enabling unacceptable options to be removed earlier. By removing these options nugatory, but time-consuming, combinations and down selections could be avoided.

8.3.2 Concurrently Assessing Different Styles

Importantly, the Library Based approach offers the potential to concurrently assess options with differing styles. The designer could benefit, when applying the Library Based approach, by examining a library containing sub-options with differing styles. Such a capability would allow the designer to gain assurance of what styles might be acceptable and, potentially, insights on how certain requirements remove particular styles as acceptable alternatives. Figure 8.2 shows how information of this type could inform the designer of acceptable styles. In this case acceptable balanced and loosely-balanced options exist for the Monohull and Trimaran (as shown in Figure 8.2a and 8.2b) but not for the Catamaran (as shown in Figure 8.2c). From this the designer could infer that the catamaran hull-form is poorly suited to the particular combination of requirements and payload that were examined.



(a) Monohull (b) Trimaran (c) Catamaran

Figure 8.2: Illustrative Plot of Output from the Library Based Approach showing its potential for comparing options with differing Styles

Case IV (presented in Section 7.4) demonstrated the application of the Library Based approach to such a library containing multiple styles. In this case the library contained Float sub-options with Monohull, Trimaran and Catamaran style and, additionally, several different styles of Move sub-options. Figure 8.3 shows the results of Case IV which demonstrated how the Library Based approach was able to examine these styles concurrently and provide information allowing a designer to infer that the Catamaran is poorly suited to the requirements and payload examined in Case IV (i.e. the LCS requirement).

8.3.3 A Discrete Library and its Size

While the Library Based design approach is considered to provide a powerful tool for the designer to explore alternatives early in the design process, its current implementation is presently limited to a discrete library of options. Section 5.2.1, which introduced the Library Based approach, highlighted two significant disadvantages of a discrete library:

- A large number of variables within any design will be continuous (i.e. length), however, the library only contains a finite number of discrete points;
- There will be limits on the extent of the solution space that sub-options within the library can represent.

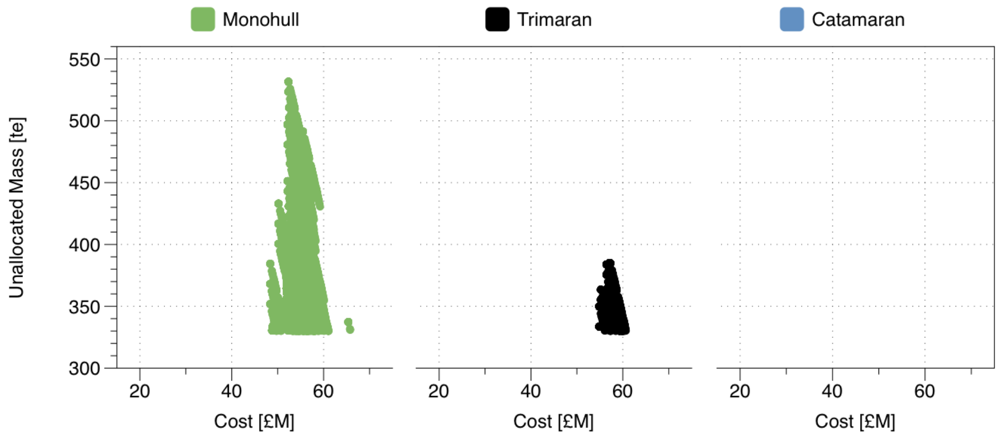


Figure 8.3: Procurement Cost vs. Unallocated Weight for Remaining Combined Float-Move-Infrastructure Options for Case IV at the conclusion of Action E, showing Hullform Styles (Repeat of Figure 7.18a)

Potential options will exist both between the options within the library and beyond the bounds of the library[3]. These two factors are recognised as significant limitations to a Library Based approach. A large number of options stored in a discrete library can provide an approximation of a continuous variable, however this requires a very large number of options to be generated and stored. Furthermore, increasing either the range or the granularity of the library rapidly increases the number of options. Consequently, the current Library Based design approach does not provide a wholly satisfactory mechanism for dealing with continuous unbounded variables. However, the current mechanism is adequate for the rapid studies the Library Based design approach is intended to be used for exploring the styles of potential options, as discussed in Section 5.4.

Given this, there is a case for increasing the size of the library, so it would be better able to describe the solution space it represents (i.e. to better represent those variables that are continuous). An examination of the library's performance was undertaken (see Section F.2 of Appendix F) which considered the differing speeds of execution for varying library sizes. This showed that the library's performance scaled well until computer hardware limitations (i.e. memory size) were encountered. One cause of growth in library size is the desire for more options differentiated by a larger number of independent variables. A second cause of growth in library size is a desire for increased granularity within the library, achieved by assessing more values for each independent variable when generating sub-options. Erikstad [1996] highlights how the 'curse of dimensionality' causes a library to quickly grow to an unmanageable size as the number of options and characteristics increases. As the number of options stored within the library grows, the time required to fetch sub-options from the library will increase. The number of options produced by a Combine Action is also likely to

[3]This is also true for the combined options generated from sub-options selected from a discrete library.

grow to an unmanageable size, given that the number of combined options is proportional to the product of the number of input items. This gives rise to a combinatorial explosion where an increase in the number of sub-options leads to the generation of a far larger number of possible combined options which then need to be evaluated.

One possibility for further development of the Library Based approach is to explore extensions to the approach that would assess options either between existing solutions in the library or at the extremes of the library. One possible solution may be to extend the Library Based method by partially adopting Hatchuel and Weil's C-K theory [Hatchuel and Weil 2003], discussed in Section 4.2.1. Specifically, Hatchuel and Weil describe C-K theory in terms of an iterative, dynamic process that steps between a Concept space (C) and a Knowledge space (K) which was illustrated in Figure 4.9.

The Library Based approach explored in this research has examined options both as a means of exploring concepts and of developing knowledge. It seems plausible that an adaptation of C-K theory, which incorporates an Option space (O) containing a library of potential options, could form a bridge between the Concept (C) and Knowledge (K) spaces of Hatchuel and Weil's C-K theory.

Expert systems, discussed in Section 3.2.5, able to utilise a changing and developing knowledge base are potentially powerful solutions to the problem of both developing and managing a knowledge base and then translating this into a number of options. It is less clear how a set of options could be taken and described in terms of a number of suitable 'concepts' that could then be combined and down selected. However, a number of methods exist which are able to map a set of distinct options into an abstract 'concept-set'[4]:

- Employing an appropriate training algorithm (e.g. a Support Vector Machine [Shawe-Taylor and Cristianini 2004]) to build a classification model[5] able to predict whether a new design description is acceptable, given the current requirements. This description could then be used to rapidly explore points in the solution space;
- Response surface methods [Price 2002b] could be used to estimate the performance of options in areas where definition is lacking;
- Rough or fuzzy set theory has the potential to be used to provide a less distinct description of the options [Alisantoso and Khoo 2009; Singer 2003] where this might be appropriate with 'softer' style issues.

[4] As defining in Section 4.2.1 on page 105.

[5] The Support Vector Machine is one example of a machine learning procedure able to group individual items based on quantitative information about one or more characteristics inherent in the items, using guidance from a training set of previously labelled items. The application of this group of machine learning procedures is commonly referred to as statistical classification [Shawe-Taylor and Cristianini 2004].

8.4 Technical Implementation Issues

Andrews' need (see Table 8.2) for concept design approaches to be 'open' could be satisfied via a Library Based approach as the methods used, to generate the library data and assess combined options, are simple and are left under the designer's control. However, there may be advantages in adopting other approaches to assess performance. Furthermore, developments to the option generation and data management techniques, employed in the improved implementation of Chapter 7, could offer advantages. These topics are discussed in Sections 8.4.1 to 8.4.2.

8.4.1 Performance Prediction

The performance of options was assessed in two separate ways during this research. Sub-options were assessed using several external performance prediction tools, as detailed in Section 7.4.1 (and Appendix H). When sub-options were combined, other simpler performance prediction methods were used to assess the vessel's performance. Separating the time intensive calculations of the sub-option's performance from the rapid calculations, necessary when combining sub-options, allowed options to be assessed more rapidly. There may be advantages in allowing the more time intensive tools to validate the simpler performance prediction methods (i.e. employing an appropriate finite element analysis code to ensure the structural proposed by simpler synthesis methods is acceptable), however this topic has not been explored within this research.

8.4.2 Option Generation

The methods used to generate the sub-options were basic and significant manual modifications were required to define sub-options of different styles. This was required even though substantial effort has been expended in developing parametric models (where a limited number of parameters define the form of a design) that were intended to be able to represent and assess a large number of different design options. Methods able to facilitate the more rapid generation and assessment of sub-options of different styles would be highly desirable. The types of parametric models described in [Cooper et al. 2007] and [Horner 2009] provide an avenue for further development to be undertaken, however considerable further work remains on developing parametric design tools able to generate sub-options from a limited number of inputs.

The parametric models developed during this research were only used to generate data on the characteristics, performance and procurement cost of options. However, [Betts 2000] identified the importance of assessing risk and through life cost in naval ship design; the implementations of the Library Based approach presented have not been used to explore these wider issues.

Finally, in regard to option generation it is also worth remarking that the topic of hullform style, which dominated this research, is just one example of style; other aspects of ship style (e.g. machinery style, structural style, layout style) are likely to have a significant effect upon the range of options available to the designer. Some of these areas (e.g. detailed general arrangement) are currently more easily undertaken by human designers and the direct application of a Library Based approach to these areas seems to present few opportunities in the near future. However, if the Library Based approach were employed by a design team who had adopted a Set Based Design strategy then assistance could be offered to the designer by keeping options open in specific areas where the Library Based approach would be easy to apply.

8.4.3 Data Management

While developing the improved implementation, an early decision was made to employ an object-relational database which models the options as objects connected via relationships (as described in Section 7.2). This model allowed the adoption of a flexible method for describing multiple styles for the options and sub-options stored in the library. Section F.2 of Appendix F is considered to demonstrate that an implementation, based upon an object-relational database, provides an acceptable level of performance. However, one disadvantage of the object-relational database is that it incurs an overhead when the program accesses information from the relational database containing the library and then translates this into the objects used by the program. The Core Data framework (described in Section F.1.6 of Appendix F), that was employed as a key technical part of the improved implementation of the Library Based tool, provides a powerful data management technique, however certain limitations were discovered in its use.

Examining the execution of the improved implementation, using code profiling tools, highlighted that a significant portion of the improved implementation's run-time is dedicated to querying the database (stored on the computer's hard drive) to retrieve the characteristics related to a single option. It is significantly faster to retrieve information directly from objects stored within the computer's random access memory. While the Core Data framework employs effective mechanisms for caching information, after it is retrieved from the database, this initial retrieval process can incur significant performance penalties. Additionally, any queries to the database must be carefully structured to ensure a rapid response; some early versions of this implementation, with poorly structured queries, took considerable time to return the objects of interest (e.g. more than an hour for a simple query).

These difficulties arose because of the different computational paradigms employed within a relational database and an object oriented programming approach. One alternative approach, that may provide considerable advantages, is an object database (such as 'db4o' [Paterson et al. 2006]). An object database allows objects to be directly stored and queried without any translation to a relational database structure. However, it is difficult to predict how the performance of any particular database technology or implementation will scale (particularly if database tasks are split across many processors or networked computers) without developing a substantial test data set[6]. The improved implementation presented in Chapter 7 has been designed around an object relational database. If there was a desire to maximise performance then it may be necessary to employ an object database and adopt an alternative object structure more focused on speed (but at the cost of flexibility). Some alternative object based structures are discussed in [Erikstad 1996].

The sub-options presented in Case V contained a large number of characteristics (e.g. the Float sub-options each had up to 70 characteristics). As any request for a given characteristic may involve checking each characteristic, this creates significant inefficiencies if a large set of characteristics has to be traversed. Alternatively adopting a library in which options are further decomposed (i.e. into sub-sub-options) may reduce the number of characteristic each decomposed options possesses. Which could in turn reduce the effort required to generate and search through the options that are stored in the library while still allowing a broader range of combined options to be developed.

8.5 Other Issues

A number of other issues have emerged during the exploration of the Library Based tool. These issues impact the approach's response to two of Betts' needs (see Table 8.1) to be usable by a knowledgeable design team and to assist communication within the design team and with stakeholders. They also impact on three of Andrews' needs (see Table 8.2) to provide coherent solutions, open methods and to be revelatory. These needs are related to the complexity of the approach and the method by which the Library Based approach provides feedback to the designer. These issues are discussed in Section 8.5.1 and 8.5.2.

8.5.1 Complexity of the Approach

Although the Library Based approach is conceptually different from existing design methods, the idea upon which it is based is not complex. A carefully developed implementation of the Library Based approach could be easy for a designer to begin using. This would allow a new user to rapidly develop their understanding at the outset of the Library Based design process. The Library Based tool also has the advantage that it could act as a central repository of design information within a large design team (or organisation). The results of design studies or sub-option studies could be added to the library over time, allowing the design team to retain and develop an extensive body of design knowledge, however

[6] Suitable test data would contain data representative of the large range of options that may be of interest to a design organisation.

the consequential issue of ensuring data validity in a large and disparate design knowledge base would still exist.

8.5.2 Feedback to the Designer

One substantial benefit of the Library Based approach is seen to be the rich variety of design data which it can store. For example, the current implementation stores sub-option information, such as ship motions and power-speed data, that allows the designer to gain insights into the performance of the ship. Such data can provide the designer with information on the likely performance achievable by a range of sub-options. As this data is pre-generated the designer can rapidly access it, obtaining design information normally not available until later in the design process. This has the potential to help guide designers as they explore options, especially at the outset of the design process. Feedback from a Library Based tool can be provided via several different mechanisms. Two key feedback mechanisms are numerical and visual feedback.

Numerical Feedback

Using a Library Based tool with an appropriate library, such as that presented in Section 7.4, could give the designer significant information on the options still possible. Useful data presentation methods include:

- Tables, presenting detailed numerical data;
- Graphs, highlighting the relationship between numerical data;
- Process Diagrams, demonstrating how options evolve through the design process.

While tables are effective at summarising precise data (such as the down selection shown in Table 8.3, repeated from Chapter 6) they are a poor mechanism for providing access to the large number of options explored using the Library Based approach. In contrast, graphs can provide insight into trends and patterns that appear in the design options within the Library, as shown by Figure 8.4. Other potential insights can be obtained through focusing on the combination and down selection process. Section 6.4 presented graphical descriptions of a down select process, repeated as Figure 8.5. Such figures show that a clear graphical insight can be obtained into the flow of options through the process of using the design tool and the effect of specific constraints. Figures such as this can convey design information on a whole process. Tufte argues that flow graphs, such as Figure J.1 from Appendix J, "may well be the best statistical graphic(s) ever drawn" in terms of their ability to successfully combine and display information [Tufte 2001].

Table 8.3: Requirements Applied for the Cassard Design from the Case I Design Study shown as Typical Data Obtained from the Library Based Approach (Repeat of Table 6.4)

Function	Requirement			Options Remaining
Float	Draught	<	6 m	768
	Length	<	160 m	727
	Beam	<	20 m	663
	Power at 30 knots	<	55 MW	368
Move	Procurement Cost	<	£150,000k	616
	Maximum Power	<	45 MW	476
	Minimum Power	>	25 MW	224
Infrastructure	Stores Endurance	>	35 days	18
	Number of Officers	>	14 men	8
⋮	⋮	⋮	⋮	⋮

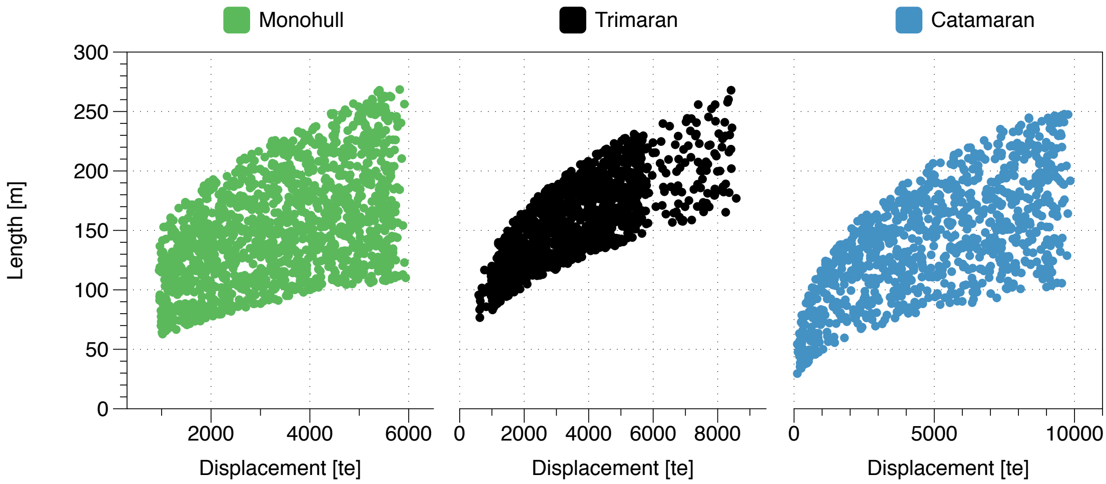


Figure 8.4: Length vs. Displacement Graph of Sub-Option Characteristics Retrieved from the Library

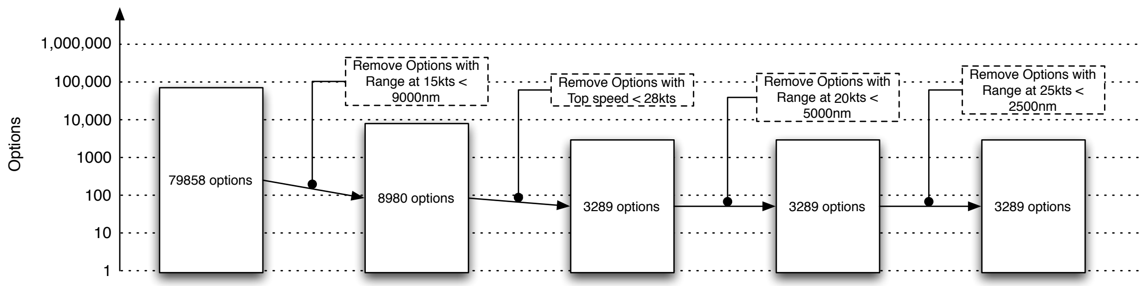


Figure 8.5: Float–Move Combined Option Down Selection Presented as an Example of the Insight Obtained through a Flow Process (Repeat of Figure 6.11)

Visual Feedback

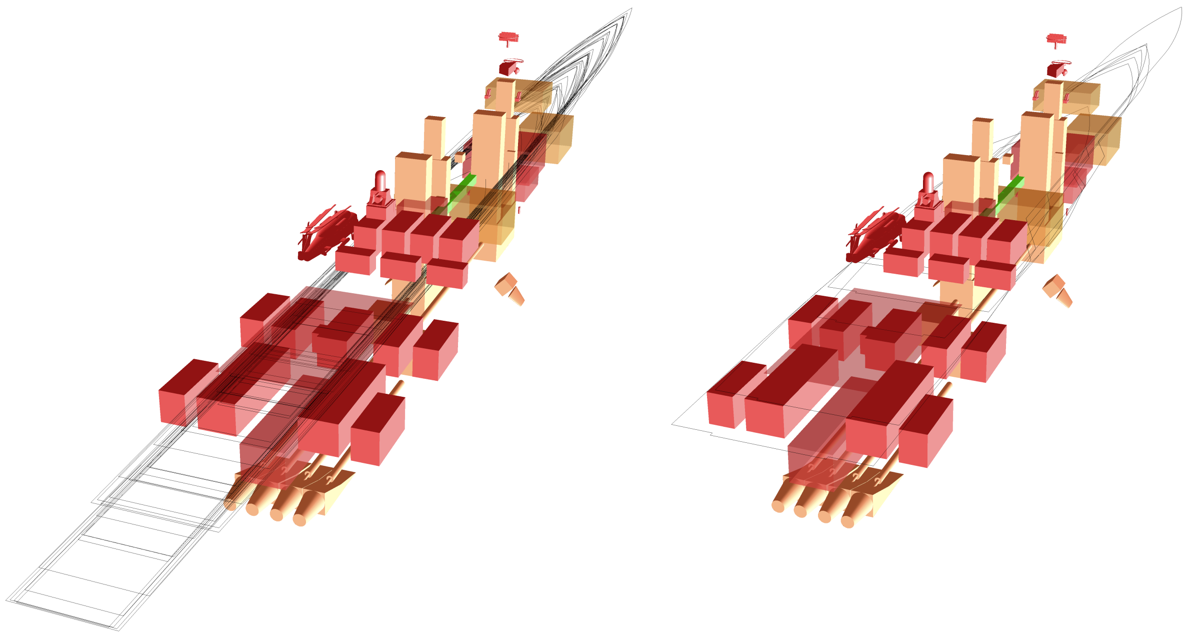
However, Andrews' requirement to demonstrate coherent solutions via a visual representation is not currently satisfied by the examples of the Library Based approach presented in Chapters 6 and 7. While a visualisation system of some type could be employed to directly display the solutions, significant resources would be required to undertake the integration necessary to provide the graphical information. An alternative to this approach—which also provides a number of other benefits—is to combine the Library Based approach with a graphically based ship design approach. The following illustrative example indicates how the proposed library tool could be used in collaboration with a different design method, namely, a design being developed using the Design Building Block (DBB) approach [Andrews and Pawling 2006].

Figure 8.6 shows how the outputs of a Library Based ship design tool could be used to better inform a designer. In this case by providing a number of outlines illustrating the gross geometry (derived from the Float sub-options in the Library Based approach) for the remaining options (i.e. those generated by the Library Based tool, which have not been removed by the designer in deciding on the requirements input) and the major Design Building Blocks[7] appropriate to the Move and Fight functional groups[8] defined using a configuration driven tool. It should be noted that none of the outlines for the monohull style options obtained from the library (shown in Figure 8.6a) present coherent solutions, given the current layout of Move and Fight Design Building Blocks; notably, the remaining options have insufficient beam at the aft of the hullform to accomodate the proposed payload layout. In comparison, at least one of the trimaran style options obtained from the library (shown in Figure 8.6b) presents a coherent solution given the current Design Building Block configuration. As the designer begins to further define and develop the design (in this case using the configuration driven tool), additional constraints will emerge, such as the need to position Fight items along the upper deck, which are likely to result in a minimum ship's length, or machinery layout, which could drive the ship's beam at certain longitudinal locations. Such constraints could then be used to further develop and constrain the feasible options, providing the designer with assurance that the design 'makes physical sense'.

Alternatively, useful information could be extracted from other performance metrics within the library and used to guide the ship's layout. For example, by examining the options or sub-options obtained using the Library Based approach, an earlier assessment of performance measures should be possible, instead of the normal approach in which such investigations are undertaken later in the design process (such as deep feasibility and full

[7] Or Super Building Block at a Super Building Block stage, see [Andrews and Pawling 2008].

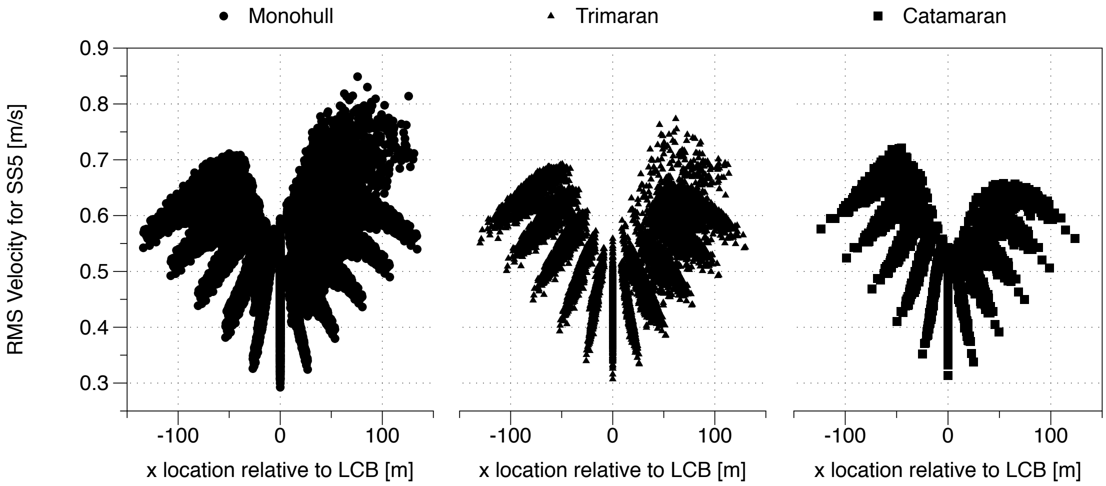
[8] Both the Fight equipment Design Building Blocks and selected Move machinery Design Building Blocks would be available early in the Design Building Block process or even already exist in the DBB 'library' (see Figure 3.3).



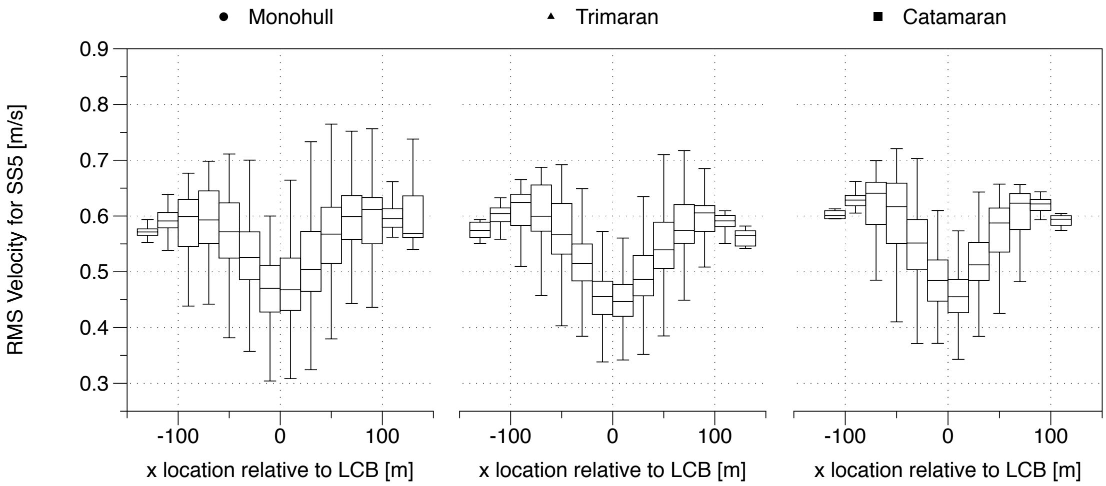
(a) Monohull Options (b) Trimaran Options

Figure 8.6: An Example of Integration of the Proposed Library Based Approach with the UCL Design Building Block Approach (showing example DBB and outlines from library data)

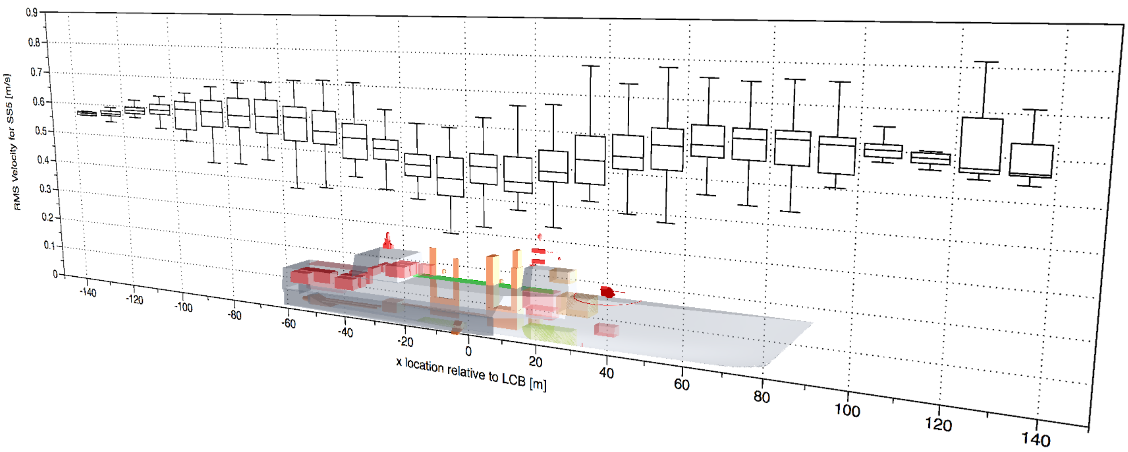
design; see discussion in Chapter 2 and 3). Figure 8.7 shows how this information could be displayed to help guide the designer in positioning systems with motion limitations (such as those required for helicopter operations). In this case, magnitude of vertical motions (Root-Mean-Squared (RMS) velocity in Sea State 5 (SS5)) relative to the distance from the hullform's longitudinal centre of buoyancy is used to identify locations that are unacceptable for certain function (such as the vessel's bridge or flight deck). Three alternative presentation formats are shown in Figure 8.7: Figure 8.7a shows the data points extracted from the library; while Figure 8.7b shows how processing this data, using a number of box plots, can provide improved guidance on the likely performance of the remaining options in the library; finally, Figure 8.7c illustrates how this data could be used to inform a designer developing a design using the DBB approach. These figures illustrates how performance data (derived from a library of options) could be used to directly guide the designer during the design process (in this example to avoid peak motions locations for sensitive evolutions). In comparison, Figure 8.6 shows an alternative mechanism for examining the solutions space, namely applying requirements to down select acceptable options whose details are then presented to the designer. These issues are also discussed in [Andrews et al. 2010] which is included as Appendix I.



(a) Point data for Float sub-options



(b) Box plot of Float Sub-options



(c) Box plot for Trimaran hullform options against a specific DBB models arrangement

Figure 8.7: RMS Velocity vs Distance from Longitudinal Centre of Buoyancy (LCB) for options from the library, from [Andrews et al. 2010]

8.6 Review of Initial Scope

Section 1.2 of Chapter 1 presented an initial scope for the thesis that has constrained this project to the early stages of the ship design process. While the implementations presented in this research have focused upon this initial stage of the design process, the discussion above has highlighted the requirement to maintain and develop interfaces with other design approaches and tools. These other aspects have largely been intended for initial ship design and so reinforce the view that the Library Based approach is primarily seen to be a tool for assisting in requirement elucidation and not one for developing detailed designs (i.e. well into Feasibility and beyond).

This research has focused upon the design of naval vessels (including those with Monohull, Trimaran and Catamaran hullforms). However, the flexibility of the improved implementation, discussed in Chapter 7, suggests the approach could be used to assess other ship styles of interest. Thus it could be useful to examine the application of the Library Based approach to the following areas:

- Additional hullform styles (e.g. SES, hovercraft, TriSWACH);
- Different types of style (e.g. various machinery fits, accommodation and ship systems configurations);
- The design of other types of naval and service vessels than the typical combatants largely addressed;
- The design of commercial ships including those that are part of a transport system (i.e. Bulk Carriers and Container Ships);
- Investigate the applicability of a Library Based design approach to the design of other large complex systems (i.e. those typically regarded as exhibiting the 'wicked problem' characteristic, see Section 2.3.3).

It is envisaged that the approach presented in this research could be easily applied to other hullform types. Many of the types of characteristics defined in the options explored using the improved implementation (e.g. weight, volume) could also be of interest for other hullforms styles. However, some different hullform styles may have alternative operating modes (e.g. SES, hovercraft). The characteristics that describe these modes must both be captured and then stored by the tool and used to correctly assess the option's suitability for the set of requirements that are of interest. Furthermore, the three types of hullform explored in the improved implementation of Chapter 7 are all displacement vessels. The application of the proposed approach to assess alternative vessel sustension styles, that are highly sensitive to changes in features or for which only a narrow range of feasible designs currently exist, has not formed part of this research and is an area for further work.

The application of the tool to the exploration of the design of other naval or service ships, particularly those where the previous adoption of a monohull configuration has led to a constrained design, is another area of significant. Potential areas of interest include:

- Manned/unmanned vehicle carriers (particularly those intending to employ conventional take off and landing arrangements);
- Offshore patrol vessels, where challenging cost constraints and limited vessel dimensions creates an opportunity where advanced marine vehicles (e.g. ACV, hydrofoils) could provide higher levels of performance.

However, to fully explore these issues it is envisaged that the Library Based approach may have to be used in combination with a complementary design approach, such as the UCL Design Building Bock approach (as discussed in Section 8.5.2).

The tools and methods produced during this research have only been developed to a proof of concept level, in order to demonstrate the Library Based approaches ability to tackle the problem of hullform selection early in the design process. Areas of further potential technical development are suggested in Section 8.4.3 and it is suggested that further research in these areas ought to be undertaken before applying the proposed approach in any 'real world' design context (i.e. beyond a teaching or research environment).

9 Conclusions

9.1 Outline

This thesis began with the identification of a gap in the design methods currently available to the designer selecting hullform style early in the ship design process. The aim of closing this gap has been achieved by defining and then addressing the concept of a new Library Based approach, which has been targeted on the early stages of naval ship design. The discussion in Chapter 8 has explored a wide range of topics related to the application of a Library Based approach to the exploration of style in preliminary ship design. There are several key conclusions that can be made from the discussion on the overall suitability of the proposed approach. This chapter presents these conclusions and then outlines proposed future development paths, which are oriented towards the aspects of the approach that are considered to provide the most potential for significant, near term improvements to the proposed approach. A more general conclusion is that the gap in the initial ship design process with regards to the selection of hullform style, identified in Chapter 1, can be met through the application of the Library Based approach, as is presented in Chapter 5 and demonstrated in Chapters 6 and 7.

9.2 Main Conclusions on a Library Based Approach for Exploring Style in Preliminary Ship Design

The exploration of style at the onset of the design process has been shown to be highly worth while. The unique decision making situation that occurs in ship concept design complicates any attempt to fully explore potential styles, even though some of these may present distinct advantages for certain design studies. Existing design approaches have been identified as being poorly suited to the rapid exploration of alternative solutions with differing styles. The consequence of this is that the designer can be prompted into an early selection of a possibly inappropriate design style before sufficient information on alternative styles has been obtained. The need for a design approach able to assist the designer in exploring these alternative styles was identified as a gap in the current preliminary ship designers toolkit.

The Library Based approach has been proposed as a means of rapidly exploring different styles at the onset of the design process. This approach employs combination and down selection of alternatives to examined options developed from a library of pre-generated options. The approach has been successfully demonstrated in the current thesis using the example of different hullform styles, via two implementations and against a number of alternative sets of requirements.

The current implementation of the Library Based approach is unable to provide the designer with direct exposure of relationships or drivers that are acting during the the design process. The usefulness of the approach would improve considerably if it was to be extended to allow feedback to the designer in such areas.

From an organisational perspective the Library Based approach could readily act as a central repository of concept design information, which would present an opportunity for a design organisation to improve their design data collection. A large diverse library of options, coupled with a tool employing the Library Based design approach could provide a designer with rapid insights into the possible consequences arising from the selection of particular styles. Importantly, this could occur before considerable design effort has been expended, however, the challenges related to creating and managing an appropriate library are seen to be significant.

The discussion in Chapter 8 addressed the advantages that could be obtained from linking the Library Based approach to other design approaches, particularly those which could provide visual insights beyond the purely numerical aspects of the design. Such a link is seen as critical if a comprehensive dialogue with the customer is to become fully incorporated into preliminary ship design practice.

9.3 Future Developments

Recommended areas for further development arising from the discussion in the preceding chapter are seen to be:

- The assessment of alternative technologies, such as object databases, for storing and accessing information within the library (as discussed in Section 8.4.3);
- The extension of the approach to provide the designer with exposure of relationships or drivers that are acting during the design process and hence give insight and explanation to the designer, clustering provides one promising development route the should be explored (as discussed in Section 8.2.2);
- The exploration of extensions to the approach to enable the assessment of options either between existing points in the library or at the extremes of a library of designs and sub-options. Hatchuel and Weil's C-K theory is seen as one possible framework that could be combined with the Library Based approach to allow the assessment of these new options, however a method able to provide this link has not been se-

lected, although three promising alternative have been identified (as discussed in Section 8.3.3);

- The investigation of parametric design tools that may simplify the generation of options, such as the Paramarine–MODEFrontier based parametric ship synthesis tool described in [Cooper et al. 2007] and [Horner 2009] (as discussed in Section 8.4.2);
- Further development of links between the Library Based approach and the UCL configuration based (DBB) approach to explore the potential of the combined approach as outlined following the initial demonstration of this research (as discussed in Sections 8.2.3 and 8.5.2 and illustrated in Figures 8.6 and 8.7).

References

AITKEN, A AND JONES, S. 'What Price Navalisation in Military Support Ships?' In 'Conference on Military Support Ships', RINA, London, November 2007.

ALISANTOSO, D AND KHOO, L. 'Early analysis of design concepts using rough set theory'. *International Journal of Systems Science*, volume 40(2):121–130, February 2009.

ANDREWS, DJ. 'Creative Ship Design'. *RINA Transactions*, volume 123:447–471, 1981.

ANDREWS, DJ. *Synthesis in Ship Design*. Ph.D. thesis, University of London, 1984.

ANDREWS, DJ. 'An Integrated Approach to Ship Synthesis'. *RINA Transactions*, volume 128:73–102, 1986.

ANDREWS, DJ. 'Written Discussion to 'Optimisation techniques in ship concept design', Keane et al. [1999]'. *RINA Transactions*, volume 132:138–139, 1991.

ANDREWS, DJ. 'The Management of Warship Design'. *RINA Transactions*, volume 135:1–24, 1993.

ANDREWS, DJ. 'Preliminary Warship Design'. *RINA Transactions*, volume 136:37–55, 1994.

ANDREWS, DJ. 'State of the art report on design methodology'. In 'Sixth International Marine Design Conference (IMDC'97)', volume 2, pp. 137–187. Newcastle, UK, 1997.

ANDREWS, DJ. 'A Comprehensive Methodology for the Design of Ships (and Other Complex Systems)'. *Proceedings of the Royal Society A*, volume 454:187–211, 1998.

ANDREWS, DJ. 'Adaptability - The Key to Modern Warship Design'. In 'RINA Warship 2001 - Future Surface Warships Conference', Royal Institution of Naval Architects, London, June 2001.

ANDREWS, DJ. 'A Creative Approach to Ship Architecture'. *RINA International Journal of Maritime Engineering*, volume 142, September 2003a.

ANDREWS, DJ. 'Marine Design - Requirement Elucidation rather than Requirement Engineering'. In 'Eighth International Marine Design Conference (IMDC'03)', 2003b.

Andrews, DJ. 'Fast Motherships - A Design Challenge'. In 'Warship 2004: Littoral Warfare & the Expeditionary Force Conference', RINA, London, June 2004.

Andrews, DJ. 'Discussion on 'Project Management of Early Stage Warship Design' by Stratmann et al.' *International Journal of Maritime Engineering*, 2006.

Andrews, DJ and Brown, DK. 'Cheap Warships Are Not Simple'. In 'Symposium on Ship Costs and Energy', SNAME, New York, Sep 1982.

Andrews, DJ, Burger, D and Zhang, J. 'Design for production using the design building block approach'. *RINA Transactions*, volume 144, 2005.

Andrews, DJ, Cudmore, A, Humble, P and Wilson, D. 'SUBCON - A new approach to submarine concept design'. In 'RINA Warship '96 - Naval submarines', Royal Institution of Naval Architects, London, June 1996.

Andrews, DJ and Dicks, C. 'The Building Block Design Methodology Applied to Advanced Naval Ship Design'. In 'Sixth International Marine Design Conference (IMDC'97)', 1997.

Andrews, DJ, Keane, RG, Lamb, T, Sen, P and Vassalos, D. 'State of the Art Report: Design Methodology'. In 'Ninth International Marine Design Conference (IMDC'06)', volume 1. Ann Arbour, Michigan, May 2006.

Andrews, DJ, McDonald, TP and Pawling, RG. 'Combining the Design Building Block and Library Based Approaches to improve Exploration during Initial Design'. 2010. In press.

Andrews, DJ, Papanikolaou, A, Erichsen, S and Vasudevan, S. 'State of the art report on design methodology'. In 'Tenth International Marine Design Conference (IMDC'09)', (SO Erikstad, ed.), volume 2, pp. 537–577. Trondheim, Norway, May 2009.

Andrews, DJ and Pawling, R. 'The Application of Computer Aided Graphics to Preliminary Ship Design'. In 'Ninth International Marine Design Conference (IMDC'06)', volume 2. Ann Arbour, Michigan, May 2006.

Andrews, DJ and Pawling, R. 'Design of a Joint Support Ship'. In 'Warship 2007', RINA, Bath, England, June 2007.

Andrews, DJ and Pawling, RG. 'A Case Study in Preliminary Ship Design'. *RINA Transaction*, volume 150:175–198, 2008.

Apple. *Core Data Programming Guide*. Apple Computer, Cupertino, CA,, 2008a. URL `http://developer.apple.com/documentation/Cocoa/Conceptual/CoreData/CoreData.pdf`.

Apple. *The Objective-C 2.0 Programming Language*. Apple Computer, Cupertino, CA,, 2008b. URL `http://developer.apple.com/documentation/Cocoa/Conceptual/ObjectiveC/ObjC.pdf`.

Apple. *Threading Programming Guide*. Apple Computer, Cupertino, CA,, 2008c. URL `http://developer.apple.com/documentation/Cocoa/Conceptual/CoreData/CoreData.pdf`.

Ashby, M, Brechet, Y, Cebon, D and Salvo, L. 'Selection strategies for materials and processes'. *Materials and Design*, volume 25(1):51–67, 2004.

Atzeni, P, Ceri, S, Paraboschi, S and Torlone, R. *Database Systems: Concepts, Languages and Architectures*. McGraw-Hill Publishing Company, Maidenhead, Berkshire, England, 1999.

Baade, R, Klinge, F, Lynaugh, K, Woronkowicz, F and Seidler, K. 'Modular outfitting'. *Journal of Ship Production*, volume 14(3):170–179, 1998.

Balasubramanian, S and Lavis, DR. 'Whole Ship Impact Assessment of Mission and Subsystem Choices for Sealift Ships'. In '24th Meeting of the U.S.-Japan Marine Facilities Panel', Honolulu, Hawaii, U.S.A, 2001.

Barone, M and Bertorello, C. 'Design Optimisation of a Trimaran Hull by Multi-attribute Concept'. In '9th Symposium on Practical Design of Ship and Other Floating Structures', Luebeck-Travemuende, Germany, September 2004.

Bayliss, J. *A methodology for topside design and integration in preliminary warship design*. Ph.D. thesis, University of London, 2003.

Benford, H. 'The Changing Scene in Marine Design Techniques'. In 'Symposium on Advances in Marine Technology', Trondheim, Norway, 1979.

Bentley, PJ (ed.). *Evolutionary Design By Computers*. Morgan Kaufmann, San Francisco, CA, 1999.

Bernstein, JI. *Design Methods in the Aerospace Industry: Looking for Evidence of Set-Based Practices*. Master's thesis, Massachusetts institute of Technology, 1998.

Bertram, V. *Practical Ship Hydrodynamics*. Butterworth-Heinmann, Oxford, 2000.

Betts, CV. 'A Review of Developments in Swath Technology'. In 'Swath ships and Advanced Multi-hulled Vessels II Conference', volume 1. RINA, London, November 1988.

Betts, CV. 'Development in Ship Design from a Naval Perspective'. In 'Seventh International Marine Design Conference (IMDC'00)', Kyongju, Korea, May 2000.

BINNS, SD. 'Meeting the Current Challenge of Designing High Capability SSK's'. In 'Warship 2008: Naval Submarines 9 Conference', RINA, Glasgow, June 2008.

BIRAN, AB. *Ship Hydrostatics and Stability.* Butterworth-Heinemann Ltd, Oxford, 2003.

BIRMINGHAM, R, CLELAND, G, DRIVER, R AND MAFFIN, D. *Understanding Engineering Design: Context, Theory and Practice.* Prentice Hall, London, 1996.

BIRMINGHAM, RW AND WILCOX, JAD. 'Charting the Links between Material Selection and Elemental Form in Structural Design'. *Journal of Engineering Design*, volume 4(2):127–140, 1993.

BRAHA, D AND MAIMON, O. 'The Design Process: Properties, Paradigms, and Structure'. *IEEE Transactions on Systems, Man, and Cybernetics - Part A Systems and Humans*, volume 27(2):146–166, 1997.

BRAS, B, SMITH, WF AND MISTREE, F. 'The Development of a Design Guidance System for the Early Stage of Ship Design'. In 'CFD and CAD in Ship Design', (Gv Oortmereeen, ed.), pp. 221– 231. Elsevier Science Publishers B.V., Wageningen, The Netherlands, 1990.

BROADBENT, C AND KENNELL, C. 'Monohull Catamatan, Trimaran and SES High Speed Sealift Vessels'. In 'RINA Fast 2001 Conference', Royal Institution of Naval Architects, Southampton, UK, September 2001.

BROADBENT, G. *Design in Architecture: Architecture and the Human Sciences.* Wiley, 1975.

BROWN. 'Written Discussion to 'Optimisation techniques in ship concept design', Keane et al. [1999]'. *RINA Transactions*, volume 132:138–139, 1991.

BROWN, A AND MIERZWICKI, T. 'Risk Metric for Multi-Objective Design of Naval Ships'. *US Naval Engineers Journal*, volume 116:55–71, Spring 2004.

BROWN, A AND SALCEDO, J. 'Multiple-Objective Optimization in Naval Ship Design'. *US Naval Engineers Journal*, volume 115:49–61, Fall 2003.

BROWN, A AND THOMAS, M. 'Reengineering the Naval Ship Concept Design Process'. In 'From Research to Reality in Ship Systems Engineering Symposium', ASNE, Tyson's Corner, VA, September 1998.

BROWN, DK. *A Century of Naval Construction: The History of the Royal Corps of Naval Constructors.* Conway Maritime Press, London, 1983.

BROWN, DK. *An Overview of Surface Warship Design Practice.* Department of Mechanical Engineering, University College London, 1996. Second Edition Revised by D.J. Andrews and D. Fellows.

Brown, DK and Andrews, DJ. 'The Design of Cheap Warships'. In 'Proceedings of the International Naval Technology Expo 80,', Rotterdam, 1980.

Brown, DK and Moore, G. *Rebuilding the Royal Navy: Warship Design Since 1945*. U.S. Naval Institute Press, Annapolis, Maryland, 2004.

Burcher, R and Rydill, L. *Concepts in Submarine Design*. Cambridge University Press, 1994.

Butler, EA. 'The Surface Effect Ship'. *US Naval Engineers Journal*, volume 97:200–253, 1985.

Buxton, IL. 'Engineering Economics Applied to Ship Design'. *RINA Transactions*, volume 114:409–428, 1972.

Carlson, C. 'Ship-to-Shore Connector (SSC) Analysis of Alternatives Overview'. In 'ONR/NAVSEA Ship Design Process Workshop', NSWC, Carderock, MD, March 2009.

Clark, DJ, Ellswotth, WM and Meyer, JR. 'The Quest for Speed at Sea'. Naval Surface Warfare Center Technical Digest, April 2004.

Clausen, HB, Lutzen, M, Friis-Hansen, A and BjÃžrneboe, N. 'Bayesian and Neural Networks for Preliminary Ship Design'. *Marine Technology*, volume 38(4):268–277, 2001.

Cocodia, E. 'The application of Fuzzy Logic and Artificial Neural Networks to Parametric Cost Estimating of Floating Offshore Structures'. *International Journal of Maritime Engineering*, volume 38:19–26, 2005.

Colton, T. 'The Marine Industry'. In 'Ship Design and Construction', (T Lamb, ed.), volume 1, chapter 3, pp. 3.1–30. The Society of Naval Architects and Marine Engineers, Jersey City, NY, 2003.

Cooper, SL, Burger, DPG and McDonald, TP. 'Concepts for a Fleet Tanker: An Exploration into Options and Pricing'. In 'Conference on Military Support Ships', RINA, London, November 2007.

Cross, N. *Engineering design methods : strategies for product design*. Wiley, Chichester, 3rd edition, 2000.

Daley, J. 'Design creativity and the understanding of objects'. *Design Studies*, volume 3:133–137, 1982.

Darke, J. 'The primary generator and the design process'. *Design Studies*, volume 1:36–44, 1979.

DELATTE, B AND BUTLER, A. 'An Object-Orientated Model for Conceptual Ship Design Supporting Case-Based Design'. *Marine Technology*, volume 40(3):158–167, 2003.

DICKS, C. *Preliminary design of conventional and unconventional surface ships using a building block approach.* Ph.D. thesis, University of London, 2000.

DOLTON, J AND SILVIA, P. 'Concepts for a UK Replacement Amphibious Fleet'. In 'Warship 86 Conference', volume 1. Royal Institution of Naval Architects, London, June 1986.

DONNELLY, K. 'Aesthetics in Warship Design'. The Naval Architect, June 1985. 282-285.

DUDSON, E AND GEE, N. 'Optimisation of the Seakeeping and Performance of a 40 knot Pentamaran Container Vessel'. In 'FAST 2001', 2001.

DUFFY, A AND MACCALLUM, K. 'Computer Representation of Numerical Expertise for Preliminary Ship Design'. *Marine Technology*, volume 26(4):289–302, 1989.

EAMES, MC. 'Future Naval Surface Ship'. *US Naval Engineers Journal*, 1985.

EAMES, MC AND DRUMMOND, TG. 'Concept Exploration - An Approach to Small Warship Design'. *RINA Transactions*, volume 119:29–54, 1977.

EASTON, R. 'The Modern Anti-Submarine Frigate'. In 'Warship 87', Royal Institution of Naval Architects, London, June 1987.

ECKERT, C, CLARKSON, PJ AND ZANKER, W. 'Change and customisation in complex engineering domains'. *Research in Engineering Design*, volume 15(1):1–21, 2004.

ELLIOTT, C AND DEASLEY, P (eds.). *Creating systems that work: Principles of engineering systems for the 21st century.* The Royal Academy of Engineering, 29 Great Peter Street, London, SW1P 3LW, June 2007.

ERIKSEN, JH (ed.). *NATO Standardization Agreement: Common Procedures For Seakeeping in the Ship Design Process.* NATO, December 2000.

ERIKSTAD, SO. 'Improved Concept Exploration in the Early Stages of the Ship Design Process'. In '5th International Marine Design Conference', Delft, May 1994.

ERIKSTAD, SO. *A Decision Support Model for Preliminary Ship Design.* Ph.D. thesis, The National Technical Norwegian University, Trondheim, 1996.

EVANS, J. 'Basic Design Concepts'. *US Naval Engineers Journal*, pp. 671–678, 1959.

EYRES, DJ. *Ship construction.* Butterworth-Heinemann, 5th edition, 2001.

Faltinsen, OM. *Hydrodynamics of High-Speed Marine Vehicles*. Cambridge University Press, Jan 2006.

Ferguson, ES. *Engineering and the Mind's Eye*. The MIT Press, 1992.

Ferreiro, LD. *Down from the Mountain: the birth of Naval Architecture in the Scientific Revolution, 1600-1800*. Ph.D. thesis, University of London, 2004.

Gale, PA. *Ship Design and Construction*, volume 1. The Society of Naval Architecs and Marine Engineers, Jersey City, NY, 2003.

Gates, P. 'Discussion on 'A Creative Approach to Ship Architecture' by Andrews (2003)'. *RINA International Journal of Maritime Engineering*, volume 142, September 2003.

Gates, PJ and Rusling, SC. 'The Impact of Weapons Electronics on Surface Warship Design'. *RINA Transactions*, volume 124:341–355, 1982.

GlobalSecurity. 'Littoral Combat Ship Program'. October 2006. URL `http://www.globalsecurity.org/military/systems/ship/lcs-lm.htm`.

Goel, A, Baker, C, Shaffer, C, Grossman, B, Haftka, R, Mason, W and Watson, L. 'VizCraft: A multidimensional visualization tool for aircraft configuration design'. In 'Proceedings of the 10th IEEE Visualization 1999 Conference (VIS '99)', pp. 425–428. San Francisco, CA, October 1999.

Gonzalez-Zugasti, JP, Otto, KN and Whitcomb, CA. 'Options-Based Multi-Objective Evaluation of Product Platforms'. *Naval Engineers Journal*, volume 3:89–106, 2007.

Google. 'Google Search Website'. January 2010. URL `http://www.google.com/`.

Goubault, P and Allison, J. 'Advanced Marine Surface Craft'. In 'Ship Design and Construction', (T Lamb, ed.), volume 2, chapter 44, pp. 44.1–22. The Society of Naval Architects and Marine Engineers, Jersey City, NY, 2003.

Graham, C. 'The Modern Monohull'. *US Naval Engineers Journal*, volume 97(2):65–82, 1985.

Hambleton, K, Kirkpatrick, D, Holder, I, Kimberley, D, Bragg, M, McInally, S, Weiss, A and Williams, T. *Conquering Complexity: Lessons for defence systems acquision*. The Stationary Office, 2005.

Hartley, K. 'UK Defence Research and Development Policy'. *World Defence Systems*, volume 4, 2003.

Hatchuel, A and Weil, B. 'A new approach to innovative design: an introduction to C-K theory'. In 'International conference on Engineering Design (ICED 03)', KTH, Royal Institute of Technology, Stockholm, Sweden, August 2003.

Heather, R. 'CASCADES'-ship design technology transfer in action'. In 'IEE Colloquium on Technology Transfer', p. 2. London, 1993a.

Heather, RG. 'Discussion to 'The Management of Warship Design', by Andrews [1993]'. *RINA Transactions*, volume 135:1–24, 1993b.

Helvacioglu, S and Insel, M. 'A reasoning method for a ship design expert system'. *Expert Systems*, volume 22(2), 2005.

Hodge, C and Mattick, D. 'The Electric Warship'. *Transaction of Institution of Marine Engineering*, volume 108(2):109–125, 1996.

Holtrop, J. 'A Statistical Reanalysis of Resistance and Propulsion Data'. *International Shipbuilding Progress*, volume 31(363):272–276, November 1984.

Horner, D. 'Design Space Exploration Using Paramarine and modeFRONTIER'. In 'ONR/NAVSEA Ship Design Process Workshop', NSWC, Carderock, MD, March 2009.

Horváth, I. 'A Treatise on Order in Engineering Design'. *Research in Engineering Design*, volume 15(3):115–181, 2004.

Hoset, K and Erichsen, S. 'General Design Theory and its Influence on Design of Ships'. In 'Sixth International Marine Design Conference (IMDC'97)', pp. 103–126. Newcastle, 1997.

Insel, M. 'Design Techniques for Advanced Marine Vehicles: Handout 1'. Faculty of Naval Architecture and Ocean Engineering, Istanbul Technical University, 2000.

International Maritime Organization. 'International Convention for the Prevention of Pollution from Ships (MARPOL)'. 1992.

Janes. 'Cassard Class'. In 'Janes Fighting Ships 2003-2004', (S Saunders, ed.), p. 226. Janes Information Group, 2003.

Jaquith, P, Burns, RM, Duneclift, L, Gaskari, M, Green, T, Silveira, J and Walsh, A. 'A parametric approach to machinery unitization in shipbuilding'. *Journal of Ship Production*, volume 14(1):59–84, 1988.

John, P. 'Acquiring capability through solution inderpendent requirements - a help or a hinderance?' In 'Defence Capability Analysis Conference', RMCS Shrivenham, April 2002.

Karayannis, T and Molland, AF. 'A decision making model for alternative high speed Ferries'. In 'RINA Fast 2001', Royal Institution of Naval Architects, Southampton, UK, September 2001.

Kaufman, L and Rousseeuw, P. *Finding Groups in Data: An Introduction to Cluster Analysis. Wiley's Series in Probability and Statistics*. John Wiley and Sons, New York, 2005.

Keane, AJ, W.G.Price and Schachter, RD. 'Optimisation techniques in ship concept design'. *RINA Transactions*, volume 132, 1991.

Kennell, CG, White, BL and Comstock, EN. 'Innovative Naval Designs for North Atlantic Operations'. *SNAME Transactions*, volume 93:261–281, 1985. The Society of Naval Architects and Marine Engineers.

Kimber, A and Giles, W. 'Minor Warship Roles - How technology is leading to a new vessel type'. In 'Pacific 2008', International Maritime Conference, Sydney, Australia, January 2008.

Kimber, A, Giles, W and Dinham-Peren, T. 'The globally deployable minor warship - A conceptualisation of future solutions'. In 'International Naval Engineering Conference', IMarEST, Hamburg, Germany, April 2008.

Kroes, P. 'Technological explanations: the relation between structure and function of technological objects'. *Techne: Research in Philosophy and Technology*, volume 3(3):18–34, Spring 1998. URL `http://scholar.lib.vt.edu/ejournals/SPT/v3n3/pdf/KROES.PDF`.

Kroes, P. 'Design methodolgy and the nature of technical artefacts'. *Design Studies*, volume 23:287–302, 2002.

Lamb, T. 'Introduction'. In 'Ship Design and Construction', (T Lamb, ed.), volume 1, chapter 1, pp. 1.1–9. The Society of Naval Architects and Marine Engineers, Jersey City, NY, 2003.

Lamerton, R, Geuzou, T, Thomas, O, White, S and Leach, I. 'Naval Design Partnership Team Future Surface Combatant C1: Proposed Statement of Work for System Engineering, Platform, Power & Propulsion and Combat System Studies'. Technical report, Naval Design Partnership, May 2008.

Laverghetta, T and Brown, A. 'Dynamics of Naval Ship Design: A Systems Approach'. *Naval Engineers Journal*, volume 11(2):307–324, May 1999.

Lavis, DR and Forstell, BG. 'High-Speed Military Sealift a Re-Examination of the Options'. In 'RINA Warship 2000 - Warships for Amphibious Opperations and Minewarefare Conference', Royal Institution of Naval Architects, London, 2000.

Lavis, DR, Rogalski, WW, Jr and Spaulding, K. 'The Promise of Advanced Naval Vehicles for NATO'. *Marine Technology*, volume 27(2):65–93, June 1990.

Lawson, B. *How Designers Think: The Design Process Demystified*. Architectural Press, Oxford, UK, 4th edition, 2006.

Lazauskas, L and Tuck, EO. 'User's Guide for Michlet'. Applied mathematics report, The University of Adelaide, 1997.

Lee, K. *Principles of CAD/CAM/CAE Systems*. Addison-Wesley Longman Publishing Co., Inc. Boston, MA, USA, 1999.

Levander, K. 'System-Based Passenger Ship Design'. In 'The 4th. International Marine Systems Design Conference (IMSDC'91)', Kobe, Japan, 1992.

Levander, K. 'Innovative Ship Design: : Can Innovative Ships be Designed in a Methodological Way?' In 'Eighth International Marine Design Conference (IMDC'03)', 2003.

Lloyd, A. *Seakeeping: Ship Behaviour in Rough Weather*. Ellis Horwood Limited,, Chichester, UK, 1989.

Lloyd, A. 'The Seakeeping Design Package (SDP)'. *RINA Transactions*, volume 134:161–180, 1992.

Lloyds. 'Warship Hull Design Enquiry'. Technical report, Lloyd's Register of Shipping, London, 1988.

Lockheed Martin. 'Littoral Combat Ship, Freedom LCS 1, Sea Trials'. Online - Accessed 27/8/2008, 2008. URL `http://www.lmlcsteam.com/photo_gallery/sea_trials/index.html`.

Long, D and Johnson, S. 'Case Studies in National Security Transformation: The Littoral Combat Ship From Concept to Program'. Technical Report 7, Center for Technology and National Security Policy, National Defense University, Washington, DC, March 2007.

Lourakis, M. 'levmar: Levenberg-Marquardt nonlinear least squares algorithms in C/C++'. 2008. URL `http://www.ics.forth.gr/~lourakis/levmar/`.

Maher, ML and Tang, H. 'Co-evolution as a computational and cognative model of design'. *Research in Engineering Design*, 2003.

Manley, D. 'Warship Vulnerability Reduction and The Littoral Environment'. In 'Warhip 2004: Littoral Warfare & The Expeditionary Force', 2004.

March, L. 'The Logic of Design'. In 'Developments in Design Methodology', (N Cross, ed.), pp. 265–276. Wiley, New York, 1984.

MarineLog. 'Transformation starts'. Simmons-Boardman Publishing Corporation, New York, Feb 2003. URL `http://www.marinelog.com/DOCS/PRINTMMIII/navmar2.html`.

Maroju, S, Syamsundar, S, DeLorme, M, Vasudevan, S, Datla, R, Pennotti, M and Bruno, M. 'A value focused approach to ship design synthesis, analysis, and selection'. In 'World Maritime Technology Conference 2006 (WMTC2006)', The Institute of Marine Engineering, Science and Technology, London, 2006.

McDonald, T and Andrews, D. 'Hullform Comparison and Selection During Requirement Elucidation in the Concept Stage of the Ship Design Process'. In 'Tenth International Marine Design Conference (IMDC'09)', (SO Erikstad, ed.), volume 1, pp. 226–246. Trondheim, Norway, May 2009.

McDonald, TP, Greig, AR and Rusling, S. 'A Comparative Study of the US Navy Littoral Combat Ship'. In 'RINA Conference on the Design and Operation of Trimaran Ships', Royal Institution of Naval Architects, London, April 2004.

Meadows, GA and Meadows, LA. 'The Marine Environment'. In 'Ship Design and Construction', (T Lamb, ed.), volume 1, chapter 2, pp. 2.1–29. The Society of Naval Architects and Marine Engineers, Jersey City, NY, 2003.

Meek, M. 'The First OCL Container Ships''. *RINA Transactions*, volume 112, 1970.

Mierzwicki, TS. *Risk Index for Multi-Objective Design Optimization of Naval Ships*. MSc Thesis, Virginia Polytechnic, 2003.

Mistree, F, Smith, WF, Bras, B, Allan, J and Muster, D. 'Decision-Based Design: A Contemporary Paradigm for Ship Design'. *SNAME Transactions*, volume 98:565–597, 1990. The Society of Naval Architects and Marine Engineers.

MoD. 'Stability Standards for Surface Ships, NES 109, Part 1, Issue 4'. Technical report, Ministry of Defence, 1999.

MoD. 'DefStan 08-140 - Classification of Weight Groups for Surface Ships (Cat 3)'. April 2001.

MoD. 'The Acquisition Handbook - A Guide to Smart Procurement, 6th edition'. Technical report, Ministry of Defence, October 2005a. URL `http://www.ams.mod.uk/ams/content/handbook/maintext.pdf`. Accessed 10/11/06.

MoD. 'Warship Engineering Management Guide (WEMG)'. Technical report, Sea Technology Group, Defence Procurement Agency, Ministry of Defence, Abbey Wood, March 2005b.

Molland, AF and Karayannis, T. 'Development of a Concept Exploration and Assessment Model for Advanced Fast Marine Vehicles'. In 'Sixth International Marine Design Conference (IMDC'97)', Newcastle, UK, May 1997.

Molland, AF, Karayannis, T, Taunton, D and Sarac Williams, Y. 'Preliminary Estimates of the Dimensions, Powering and Seakeeping Characteristics of Fast Ferries'. In 'Eighth International Marine Design Conference (IMDC'03)', National Technical University of Athens, May 2003.

Moret, JA and Gee, NI. 'The Pentamaran Fast Ferry - The Ultimate Step Forward in Passenger and Cargo Transportation at High Speed'. In '17th International Fast Ferry Conference', Florida, March 2001.

Mougin, P. 'F-Script'. Online, 2006. URL `http://www.fscript.org/`.

Mougin, P and Ducasse, S. 'OOPAL: Integrating Array Programming in Object-Oriented Programming'. In 'Proceedings of the 18th ACM SIGPLAN conference on Object-oriented programing, systems, languages, and applications', 2003.

NAO. 'Providing Anti Air Warfare Capability: the Type 45 destroyer'. Technical report, National Audit Office, The Stationery Office, London, March 2009.

NATO. 'Assesment of Point Designs - Volume II: Detailed Assesment'. Technical report, NATO Armament Group Special Working Group, 1987.

NATO. 'The Application of Costing and Operational Effectiveness Methods for the Selection of Hull Types'. Technical report, NATO Armament Group Special Working Group, March 1997.

NATO. 'NATO-PfP Working Paper on Small Ship Design'. Technical report, NATO Naval Group 6, 2004.

Nethercote, W and Schmitke, R. 'A Concept Exploration Model for SWATH Ships'. *RINA Transactions*, volume 124, 1982.

Nissen, S. *Implementation of a Fast Artificial Neural Network Library*. Master's thesis, Department of Computer Science University of Copenhagen (DIKU), 2003. URL `http://fann.sf.net`.

NIST. 'NIST/SEMATECH e-Handbook of Statistical Methods,'. September 2009. URL `http://www.itl.nist.gov/div898/handbook/`.

Norman, DA. *The design of everyday things*. Basic Books, 2002.

Nowacki, H. 'Developments in Marine Design Methodology: Roots, Results and Future Trends'. In 'Tenth International Marine Design Conference (IMDC'09)', (SO Erikstad, ed.), volume 1, pp. 47–80. Trondheim, Norway, May 2009a.

Nowacki, H. 'Five decades of Computer-Aided Ship Design'. *Computer-Aided Design*, volume In Press, Corrected Proof:–, 2009b. URL `http://www.sciencedirect.com/science/article/B6TYR-4WXHBX8-1/2/1bf27efd18f3394f7833fbd799d5dddd`.

Oxford University Press. 'Oxford English Dictionary'. Online, 2006. URL `http://dictionary.oed.com/`.

Pahl, G and Beitz, W. *Engineering Design*. The Design Council, London, 1984.

Papalambros, P and Wilde, D. *Principles of Optimal Design*. Cambridge University Press, Cambridge, UK, 1988.

Park, JH and Storch, RL. 'Overview of Ship-design Expert Systems'. *Expert Systems*, volume 19(3):136–141, 2002.

Parsons, MG. 'Parametric Design'. In 'Ship Design and Construction', (T Lamb, ed.), volume 1, chapter 11, pp. 11.1–48. The Society of Naval Architects and Marine Engineers, Jersey City, NY, 2004.

Parsons, MG, Singer, DJ and Sauter, JA. 'A Hybrid Agent Approach For Set-Based Conceptual Ship Design'. In 'Proceedings of the 10th International Conference on Computer Applications in Shipbuilding', Cambridge, MA, June 1999.

Paterson, J, Edlich, S, Hörning, H and Hörning, R. *The Definitive Guide to db4o*. Apress, Berkely, CA, USA, 2006.

Pawlak, Z and Skowron, A. 'Rudiments of rough sets'. *Information sciences*, volume 177:3–27, 2007.

Pawling, RG. *The Application of the Design Building Block Approach to Innovative Ship Design*. Ph.D. thesis, University College London, 2007.

Peirce, C. 'The Collected Papers of Charles Sanders Peirce'. volume 7–8. Harvard University Press, 1958.

Peri, D and Campana, EF. 'Multidisciplinary Design Optimization of a Naval Surface Combatant'. *Journal of Ship Research*, volume 47(1), 2003.

Perl. 'The Perl Directory at Perl.org'. Online, 2009. URL `http://www.perl.org/`.

Phillips, SJ (ed.). *Jane's High Speed Marine Transportation.* Jane's Information Group Limited, Coulsdon, Surry, UK, 1999.

Press, W, Flannery, B, Teukolsky, S and Vetterling, W. *Numerical Recipies: The Art of Scientific Computing.* Cambridge University Press, 1986.

Price, S. 'Revised Mathcad Ship Synthesis Model'. Technical report, Naval Construction and Engineering Program, XIIIA, Ocean Engineering Department, Massachusetts Institute of Technology,, 2002a.

Price, SL. *Integrating Response Surface Methods and Uncertainty Analysis into Ship Concept Exploration.* MSc Thesis, Massachusetts Institute of Technology, 2002b.

Psillos, S. *Philosophy of Science A-Z.* Edinburgh University Press, 2007.

Rawson, KJ. 'Marine System Design Methodology'. In 'International Symposium on Advances in Marine Technology', pp. 25–41. Trondheim, Norway, 1979.

Rawson, KJ and Tupper, EC. *Basic ship theory.* Butterworth-Heinemann, Boston, 5th edition, 2001.

Ray, T. 'Intelligent Concept Exploration using Artificial Neural Network Model'. SNAMES Transactions, Society of Naval Architects and Marine Engineers Singapore, 1998.

Rees, S, Reed, D, Cain, C and Cripps, B. 'Coupled Fluid-Structural Modelling of Wave Impact Loads on HSC'. In 'RINA Fast 2001', Royal Institution of Naval Architects, Southampton, UK, September 2001.

Reich, Y. 'A Critical Review of General Design Theory'. *Research in Engineering Design*, volume 7(1):1–18, 1995.

Riaz, Z, Sargeant, P, Horsted, J and Tang, K. *Anti-Air Warfare Frigate.* Ship design report, Department of Mechanical Engineering, UCL, June 2007.

RINA. 'Sea SLICE to act as littoral warfare vessel.' *Warship Technology, RINA*, p. 7, July/Aug 2002.

RINA. 'MerIT - Advanced design and analysis technology from Graphics Research Corporation Limited, U. K.' *Warship Technology, RINA*, January 2003.

RINA. *RINA Conferences on the Design and Operation of Trimaran Ships.* Royal Institute of Naval Architecture, London, UK, April 2004.

Rittel, HW and Webber, MM. 'Planning Problems are Wicked Problems'. In 'Developments in Design Methodology', (N Cross, ed.), pp. 135–144. Wiley, New York, 1984. Reprint.

Robb, MD. 'Cost Effective Naval Platforms'. In 'RINA Warships 2006 - Future Surface Warships Conference', Royal Institution of Naval Architects, London, June 2006.

Rolls-Royce plc. 'The MT30 marine gas turbine'. Accessed from the Rolls Royce website, Rolls-Royce Power Engineering plc, Filton, Bristol, England, 2009. URL `http://www.rolls-royce.com/marine/products/diesels_gas_turbines/gas_turbines/mt30.jsp`.

Rydill, LJ. 'No, the future of the Corps is not in Systems Engineering'. *Journal of the Royal Corps of Naval Constructors, Ministry of Defence, Bath*, 1969.

Sadden, JA and Nisbet, C. 'Are two hulls better than one (or three)?' In 'RINA Warship '98 - Surface Warships Conference', Royal Institution of Naval Architects, London, June 1998.

Schiller, TR, Daidola, JC, Kloeetzli, JW and Pfister, J. 'Portfolio of Ship Designs: Early-Stage Design Tools'. *Marine Technology*, volume 38(2):71–91, 2001.

Schofield, J. 'Warship Vulnerability from concept to service: SURVIVE and SURVIVE Lite'. In 'Maritime Systems and Technology Conference', Genoa, Italy, November 2007.

Sen, P. 'Marine Design: The Multiple Criteria Approach'. *RINA Transactions*, volume 133, 1991.

Sen, P and Bari, A. 'Inland Waterway Fleet Replacement: Evaluation with Multiple Objectives'. *RINA Transactions*, volume 127:205–220, 1984.

Shawe-Taylor, J and Cristianini, N. *Kernel methods for pattern analysis*. Cambridge Univ Press, 2004.

Simon, HA. *The Sciences of the Artificial*. The MIT Press, Cambridge, Massachusetts, second edition edition, 1981.

Simpson, TW, Chen, W, Allen, JK and Mistree, F. 'Conceptual design of a Family of Products through the use of the Robust Concept Exploration Method'. In 'Symposium on Multidisiplinary Analysis and Optimisation', volume 2, pp. 1535–1545. AIAA, Bellevue, WA, Sept 1996.

Singer, DJ. *A Hybrid Agent Approach for Set-Based Conceptual Ship Design through the Use of a Fuzzy Logic Agent to Facilitate Communications and Negotiation*. Ph.D. thesis, The University of Michigan, 2003.

Singer, DJ, Doerry, CN and Buckley, ME. 'What is Set-Based Design?' In 'American Society of Naval Engineers Day', National Harbor, Maryland, April 2009.

Smith, T. *Concept Design of Concept Design*. MSc Thesis, Department of Mechanical Engineering, University College London, 2004.

Smith, T. 'Generic seakeeping code'. Technical report, UCL, 2008.

Smith, W and Mistree, F. 'The Development of a Top Level Ship Specification: A Decision Based Approach'. In 'Fifth International Marine Design Conference (IMDC'94)', volume 1, pp. 59–77. Delft, 1994a.

Smith, W and Mistree, F. 'Discussion on 'The Development of a Top Level Ship Specification: A Decision Based Approach''. In 'Fifth International Marine Design Conference (IMDC'94)', volume 2, pp. 45–52. Delft, 1994b.

Smith, WF. *The Modeling and Exploration of Ship Systems in the Early Stages of Decision-based Design*. Ph.D. thesis, University of Houston, 1992.

Smith, WF, Kamel, S and Mistree, F. 'The Influence of Hierarchical Decisions on Ship Design'. *Marine Technology*, volume 24(2):131–142, April 1987.

Sobek, DK and Ward, AC. 'Principles from Toyota's Set-based Concurrent Engineering Process'. In 'ASME Design Engineering Technical Conference and Computers in Engineering Conference', Irvine, California, 1996.

Stopford, M. *Maritime economics*. Routledge, 3rd edition, 2008.

Stratmann, P, Wilson, PA, Molland, AF and Courts, MD. 'Project Management of Early Stage Warship Design'. *International Journal of Maritime Engineering*, 2006.

Suh, NP. *The Principles of Design*. Oxford University Press, 1990.

Suh, NP. *Axiomatic Design: Advances and Applications*. Oxford University Press, 2001.

Tan, K and Sen, P. 'The Application of a Decomposition and Reuse Approach in Marine Design'. In 'Practical Design of Ship and Other Floating Structures', Shanghai, China, September 2001.

Tan, KT and Bligh, TP. 'A New Approach to an Integrated CAD Method for Surface Ship Design'. *Naval Engineers Journal*, volume 110(1):35–48, January 1998.

Tibbitts, T and Keane, RG. 'Making Design Everybody's Job: The Warship Design Process'. *US Naval Engineers Journal*, 1995.

Tufte, ER. *The Visual Display of Quantitative Information*. Graphics Press USA, Cheshire, Connecticut, 2001.

UCL. *MSc Ship Design Procedure*. Department of Mechanical Engineering, University College London, 2002.

UCL. *MSc Ship Design Data Book*. Department of Mechanical Engineering, University College London, 2004.

US Navy. 'Preliminary Design Interim Requirement Document for Littoral Combat Ship (LCS) Flight 0'. Technical Report N763F-S03-026, US Navy, Febuary 2003.

US Navy. 'Graphic of Three Preliminary Concepts Designs for the Littoral Combat Ship'. Online, 2005. URL `http://peoships.crane.navy.mil`.

U.S. Navy. 'USS Independence'. May 2008. URL `http://www.navy.mil/view_single.asp?id=67111`.

Usher, P and Dorey, A. 'A Family of Warships'. *RINA Transactions*, volume 124:85–112, 1982.

van Griethuysen, WJ. 'On the Variety of Monohull Warship Geometry'. *RINA Transactions*, volume 134, 1992.

van Griethuysen, WJ. 'On the Choice of Monohull Warship Geometry'. *RINA Transactions*, volume 135, 1993.

van Griethuysen, WJ. 'Marine Design: Can Systems Engineering Cope?' In 'Seventh International Marine Design Conference (IMDC'00)', Korea, 2000.

van Hees, MT. 'Knowledge-based Computational Model Assembling'. In 'Summer Computer Simulation Conference', pp. 285–294. Society for Computer Simulation International, 2003.

van Oers, B, Stapersma, D and Hopman, H. 'Development and Implementation of an Optimisation-Based Space Allocation Routine for the Generation of Feasible Concept Designs'. In 'Proc. 5th International Conference on Computer Applications and Information Technology in the Marine Industries (COMPIT)', pp. 171–185. Cortona, Italy, 2007.

van Oers, B, Stapersma, D and Hopman, H. 'Issues when selecting naval ship configurations from a Pareto-optimal set'. In 'Presented at the 12th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference', AIAA, Victoria, British Columbia, Canada, September 2008.

Vasudevan, S. *Utility of the Pareto-front approach in elucidating ship requirements during concept design*. Ph.D. thesis, University of London, 2008.

Vasudevan, S and Rusling, S. 'A Simulation Tool Using Genetic Algorithms for Practical Ship Design'. In 'Proceedings of UKSim', Oxford, UK, 2006.

WALDEN, DA. 'Extension of the Bales Seakeeping Rank Factor'. In '20th American Towing Tank Conference', volume 2, pp. 1037–1045. Davidson Laboratory, Stevens Institute of Technology, Hoboken, New York, 1983.

WATSON, DGM. *Practical ship design*. Elsevier, Oxford, 1998.

WATSON, DGM AND GILFILLAN, A. 'Some ship design methods'. *RINA Transactions*, volume 118, 1976.

WATTS, RD. 'The Elements of Designs'. In 'The Design Method', (S Gregory, ed.), pp. 85–95. Butterworths, London, 1966.

WELSH, M, BUXTON, IL AND HILLS, W. 'The application of an expert system to ship concept design investigations'. *RINA Transactions*, volume 132, 1990.

WHITFIELD, R, HILLS, B AND COATES, G. 'The Application of Multi-Objective Robust Design Methods in Ship Design'. In 'International Conference on Computer Applications at Sea', Cambridge, MA, June 1999.

WILSON, SR. 'Introduction to Combinatorial Libraries: Concepts and Terms'. In 'Combinatorial chemistry: synthesis and application', (SR Wilson and AW Czarnik, eds.), chapter 1, pp. 1–23. Wiley, NewYork, NY, April 1997.

YEH, H. 'Series 64 resistance experiments on high-speed displacement forms'. *Marine Technology*, volume 2(3):248–272, July 1965.

YOSHIKAWA, H. 'General Design Theory and it's Application to Categorization of Ship Design'. In 'International Symposium on Advances in Marine Technology', pp. 69–89. Trondheim, Norway, 1979.

ZADEH, L. 'Fuzzy sets'. *Information and control*, volume 8(3):338–353, 1965.

Appendices

Appendix A

A Comparative Study of the US Navy Littoral Combat Ship

This appendix was published as a conference paper entitled "A Comparative Study of the US Navy Littoral Combat Ship" in the Royal Institution of Naval Architect's Conference on the Design and Operation of Trimaran Ships in London, April 2004.

A Comparative Study of the US Navy Littoral Combat Ship

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SUMMARY

An emerging United States Navy requirement for a fast Littoral Combat Ship (LCS) is currently being developed to counter asymmetric threats within the littoral, principally: mines, small fast surface craft, and diesel submarines. The LCS is described as a fast, stealthy, low cost naval combatant that leverages the potential of advanced hullforms to meet demanding performance requirements.

This paper takes the US Navy Littoral Combat Ship requirements as a baseline and then demonstrates how they might be satisfied using a range of hullforms. The advantages and disadvantages of the monohull, trimaran, surface effect ship and catamaran are explored using a numerical sizing model. Point designs are proposed which examine the feasibility of the results of the sizing model, drawing out design drivers for each hullform. Finally, conclusions are drawn as to the hullform which provides the most cost effective solution to the task of the littoral combat ship.

1 LCS CONCEPT

The change in the international landscape after the end of the Cold War has led many navies to reconsider their potential adversaries. This reassessment has identified a capability gap within the littoral environment. The US Navy (USN) has released a requirement for a flexible, agile and reconfigurable vessel to confront both conventional and asymmetric access-denial threats within the littoral environment, the Littoral Combat Ship (LCS).

The requirement for the LCS is a result of the current force structure of the USN, which is a product of the technology base and perceived threats of the Cold War. This gave rise to naval forces composed of large, expensive multimission surface combatants, capable of operating in a wide variety of roles worldwide but optimised for blue water operations. While there is no question as to the utility of these adaptable vessels they are not without drawbacks.

In a navy with only a small number of expensive surface combatants, there is a reluctance to place large ships in harms way within the littoral. This has been labelled as “tactical instability” [1] and is perceived by some to be a growing issue, particularly for the navy after next. As a consequence there is now a desire to procure “small, fast, inexpensive warships - designed to go into harm’s way and, if necessary, be lost - hunt down ... subs and missile launchers hidden among fishing boats and cargo ships” [2].

The LCS, as described in [3], provides a means of fulfilling this role through high performance, an open architecture and modularity. By providing the ship with the ability to rapidly reconfigure, it allows the USN to provide a more appropriate response to a given situation.

However, by stepping outside the range of recent naval combatants in terms of desired performance, the LCS gives rise to many challenges for designers. It poses questions as to the tradeoff between payload and performance, especially at high speeds, together with the applicability of novel ship types, such as trimarans, catamarans and surface effect ships (SES).

2 STUDY OBJECTIVE AND LIMITS

This study uses a cost-performance-capability analysis to produce results which highlight the challenging aspect of high speed craft concept design. By examining the trade off between capability to achieve a given cost target, the impact of the different performance requirements were investigated.

A second important aspect of the design process is to examine any limitations of the current concept design toolkit. A key result is the identifications of possible areas where performance prediction is not sufficiently robust.

2.1 COST-CAPABILITY ANALYSIS

The cost capability analysis explored the impact of payload and requirements on the different platforms through a numerical model. Standardised payload options and performance levels across the four different vehicles were used.

2.2 PERFORMANCE REQUIREMENTS

Performance requirements were set based upon the threshold and objective performance values found within [3] which are summarised in Table 9. By relaxing the required performance criteria the sensitivity of each design to the challenging performance requirements was found.

2.3 STRUCTURAL WEIGHT MINIMISATION

A brief exploration of the effect of changes to the structural weight of the different craft was performed. The intention was to investigate how ship designs using the four hullforms benefit from lighter structures.

3 METHOD AND MODELS

A cost benefit model is used to examine the trade off in capability of a system versus the cost of procurement. Taking the example of a multi-role frigate the combat system's offensive and defensive functions can be divided into anti-submarine, air-defence and land attack capabilities. All three capabilities are delivered through a variety of combat system elements. An improvement, such as the addition of a large gun, would enhance the ships ability to engage land targets. Some improvements assist across several categories, facilities for a second helicopter may, for instance, assist in both anti-submarine and land attack roles.

For a given matrix of different options for combat system elements there will be a path from the low to the high end of capability that gives the best value for money. This path is termed the frontier line and is illustrated in Figure 1 as the curve to the left of the datapoints.

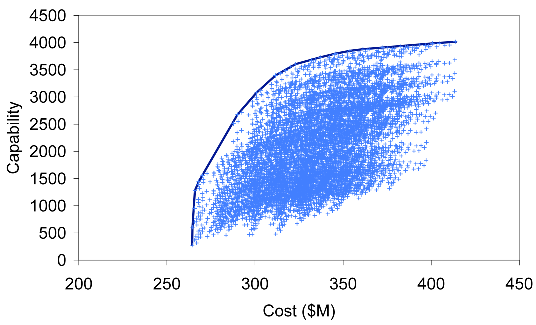

Figure 1: Example Cost-Benefit Output

However, some of the assumptions that are made during a standard cost-capability analysis are not valid for the LCS. For example the effect of payload increases upon the ship's displacement are small. This assumption was felt to be inappropriate due to the high speed of the LCS. Changes in displacement would have a large impact upon the power requirements as demonstrated by [4]. It was therefore necessary to develop a model that was representative of these requirements.

3.1 OVERALL ARCHITECTURE

The core elements of the model are the sizing, geometry and performance modules. These are distinct to each of the ship types and work together to generate a cost description for a given payload and performance requirement. The machinery selection module sits outside the ship specific elements; this is intended to provide a degree of independence for engine selection. (Figure 2)

The relatively high volumetric Froude number of the LCS created distinct problems with resistance prediction. Several different series were compared to attempt to establish the resistance, these included Holtrop [5], Mercier [6] and model test data [7]. While results for the semi-planing hullforms gave lower required powers the difficulty in extrapolating from a small set of test data led to Holtrop being adopted as the resistance prediction method. Consequently resistance estimation can be regarded as pessimistic however given the large uncertainty within the design no corrections have been attempted.

The machinery selection process determines a machinery fit that meets the ships power requirements. Propulser types and power requirements are passed for four operating condition: anti-submarine warfare; fleet operations; naval strike; and sprint (see Table 9). The final choice is the lowest weight solution, including fuel, which satisfies these four criteria.

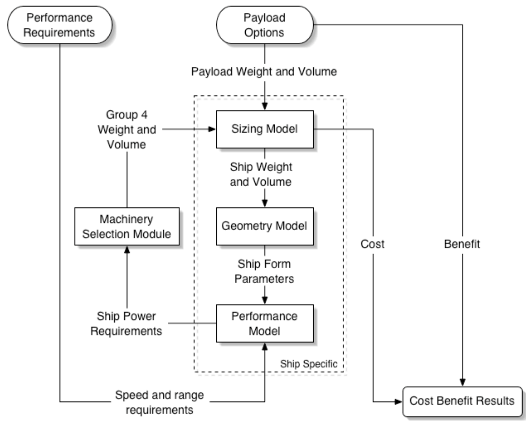

Figure 2: Cost-Benefit Program Architecture

The UCL sizing procedure is a simple weight and volume balancing process. The procedure iterates to find a ship for which the displacement equals the weight and the required volume is equalled or exceeded by the ships volume. The different elements of the ships mass and volume are divided into one of seven groups, as described in Table 1.

Basic stability and structural checks are performed within the geometry model. The stability checks ensure the GM, determined from the shape at the waterline, is sufficient. The structural checks ensure the overall ship length to depth ratio is appropriate.

Group	Item
Group 1	Ship Structure
Group 2	Personel
Group 3	Ship System
Group 4	Main Propulsion
Group 5	Electrical Systems
Group 6	Payload
Group 7	Variables

Table 1: UCL Weight Groups

4 RESULTS

The sizing model described in Section 3 was used to create a range of balanced ships that meet the LCS requirements. The sizing procedure used generated a large amount of data, far too much to present in full in this paper. The salient points of the results are presented in the following section.

4.1 COST CAPABILITY ANALYSIS OF DIFFERENT LCS HULLFORMS

Figure 3 shows the performance of the four ship types when they are designed to meet the objective performance requirements. The four curves describe the capability achievable, in relation to cost, for the four hullforms.

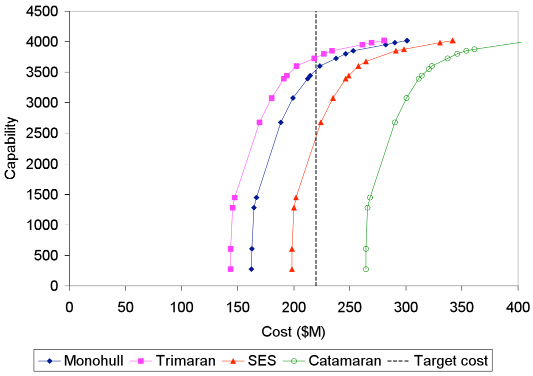

Figure 3: LCS Objective Performance Results

A simple examination of figure 3 allows the different hullforms to be ranked in terms of cost effectiveness. Simply stated, the trimaran is the most effective hullform for the task, next is the monohull, then the SES and finally, by a considerable margin, the catamaran.

The monohull, trimaran and surface effect ship all produce workable solutions at the target cost of $220M. However the catamaran is unable to meet the specified budget with a cost of $264M for the most basic configuration.

Looking at the payload options selected as one progresses along the frontier curve, the different hullforms were seen to follow a similar pattern. Table 2 contains the data points which can be seen in Figure 3 for the trimaran. It is presented to give an insight into the order which the payload improvements were selected. Too much should not be read into the values for price and displacement, they are quoted to this level to discriminate options.

All four ship types selected an increased aviation capacity (AR) then improvement in modularity (MOD) as their first two improvements. This is followed by minor improvement in sub-surface warfare (SS) outfit, then several intelligence and surveillance (IS) equipment improvements until this option was maximised. From this point on there was a slow increase in the air-defence (AD), sub-surface warfare and surface warfare (SW) until the ships reaches the full payload level examined in this study.

While the general pattern of payload improvement is similar for the different hullforms there are some differences. As described in Section 3 the method used to perform the cost-capability analysis takes into consideration the effect of rebalancing the ship and resizing the power plant.

The different types of hull respond to payload of different weights and densities in a different manner. However due to high capability values given to the larger payload items (i.e. aircraft and modular payload items), this is not an obvious feature in this analysis.

Payload Changes	Payload Groups						Capability							Price Level ($M)	Deep Disp. (tonnes)
	SW	AD	SS	IS	MOD	AR	Fast Attack Craft	Land Attack	Mine Counter Measures	Anti-Submarine Warfare	Air Defence	Intelligence	Total		
Baseline	0	0	0	0	0	0	70	110	20	20	20	35	275	143.7	2203
Second helicopter	0	0	0	0	0	1	220	260	20	20	20	65	605	143.9	2208
4 x Modular Payload Bay	0	0	0	0	2	1	220	710	200	20	20	110	1280	145.3	2289
Anecheoic Tiles	0	0	1	0	2	1	220	710	300	85	20	110	1445	147.5	2293
IR Camera Fit, Night Vision, Electro-Optic MARK 36, CEC Rx (AN/USG 2v)	0	0	1	3	2	1	510	880	300	155	330	500	2675	169.4	2297
CEC Tx	0	0	1	4	2	1	510	880	300	155	330	900	3075	180.1	2300
NULKA, RAM system	0	1	1	4	2	1	540	880	300	155	620	900	3395	191.4	2330
CIWS	0	2	1	4	2	1	540	880	300	155	670	900	3445	193.9	2349
20 mm Gun, 40 mm Gun, 76 mm Gun	2	2	1	4	2	1	650	930	300	155	670	900	3605	202.7	2382
Torpedo Launch System	2	2	3	4	2	1	650	930	300	280	670	900	3730	217.8	2521
Second RAM system	2	3	3	4	2	1	670	930	300	280	720	900	3800	226.6	2534
Second Torpedo Launch System, Depth Charges	2	3	4	4	2	1	670	930	300	330	720	900	3850	234.2	2699
2 x Surface-surface Missile, 2 x 120 mm Gun	7	3	4	4	2	1	680	1025	300	330	720	900	3955	261.3	3097
Towed Array Sonar	7	3	5	4	2	1	680	1025	300	360	720	900	3985	269.3	3151
Third RAM system, second CIWS	7	4	5	4	2	1	680	1025	300	360	750	900	4015	280.6	3183

Table 2: Trimaran Frontier Options

Figures 4 and 5 describe the weight and cost of the four solutions closest to the target cost of $220M. By examining these graphs the different drivers in the design can be inferred.

4.1 (a) WEIGHT ANALYSIS OF THE SOLUTIONS

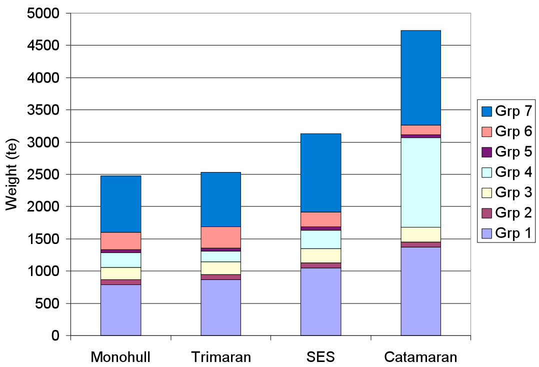

Figure 4: LCS Objective Performance Weight Breakdown

From Figure 4 it is apparent that there is a large disparity in the displacement of the solutions. This can be seen to arise mainly from Groups One (Structure), Four (Main Propulsion), and Seven (Variables). Considering each of these in turn leads us to an understanding of the reasons for the extra mass.

Both the SES and the catamaran have a larger structural weight than the monohull and trimaran. The structural mass given in Group One should be larger for a catamaran/SES when the relative surface areas of the hullforms are considered (all vessels are steel).

As the SES requires a lift system, in addition to the standard propulsion system, there will be a larger weight for Group Four. The majority of this weight is not due to the gas turbine but rather the gear boxes, lift fans and skirts. This is in part due to the decision to use four lift fans, each driven by their own prime mover, to provide redundancy and to keep the centre of the box for payload spaces.

The increase in the weight of the structure in the SES and catamaran ships leads to a larger displacement. If the speed requirement is held constant then this results in an increase in the size of Group Four. Higher power machinery will require an increase in fuel weight to meet range targets. These factors combine to cause the design's displacement to spiral up.

There is little difference between the monohull and trimaran in overall weight. As would be expected, however, the structural weight is slightly larger for the trimaran. In practice this is mitigated by a reduction in the required power causing a decrease in the weight of Group Four.

These conclusions are supported by Figure 5 which demonstrates the distribution of costs within the ship. As Group Six represent the payload, the ship with the largest fraction of the $220M target cost allocated to this group will provide the most significant increase in capability.

4.1 (b) COST ANALYSIS OF THE SOLUTIONS

Having considered the distribution of mass between the weight groups we can move on to an analysis of cost of each Group. Note that Group Seven is not costed as the pricing data available at UCL only cover build costs.

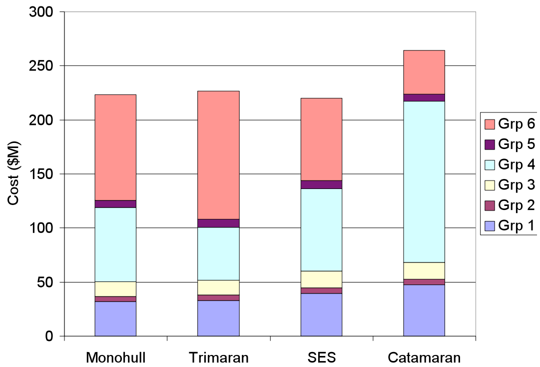

Figure 5: LCS Objective Performance Cost Breakdown

Figure 5 clearly demonstrates that, of the four solutions considered, the trimaran allows the most resources to be allocated to the payload. Next is the monohull, which requires a more expensive propulsion system. The SES requires a more complex, and hence expensive, propulsion system to cater for the power demands of the widely distributed lift system. Finally the catamaran, for which the baseline missed the cost target of $220M, can be seen to require approximately $220M for groups one to five alone, the baseline payload pushing the ship cost far beyond the target.

One interesting aspect of the cost capability comparison shown in Figure 3 is the location of the knee in the curve in relation to the different hullforms. The position of a knee in the curve indicates a point where the addition of more payload begins to result in diminishing returns in relation to payload cost.

For the monohull and trimaran the knee is at or below the target cost threshold, while the SES and catamaran the knee is far above this point. The SES and catamaran are still in the region where large improvements in capability can be achieved for a moderate increase in cost. The monohull and trimaran already posses these items, further improvement in payload take the form of the more costly items.

4.2 PERFORMANCE REQUIREMENT TRADEOFF STUDY

Changing from the objective performance requirements to the threshold requirements defined in Table 9 significantly alters the results produced by the model. The new results are presented in Figure 6.

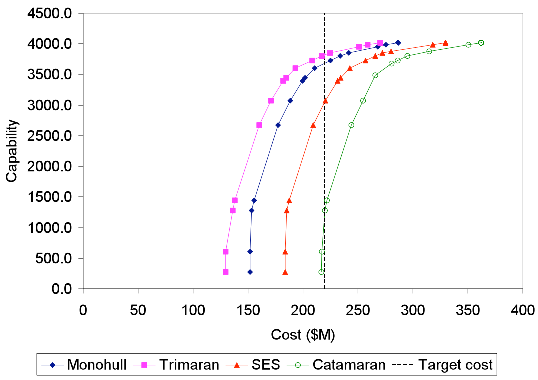

Figure 6: LCS Threshold Performance Results

Comparing Figure 6 with Figure 3, the changes brought about by the relaxation of the performance requirements are evident. All four solutions now produce viable options at the target price. (Figures 7 and 8)

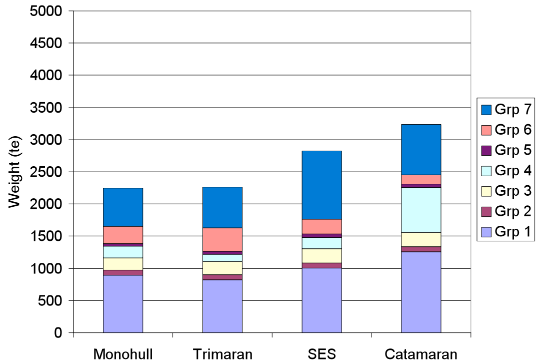

Figure 7: LCS Threshold Performance Weight Breakdown

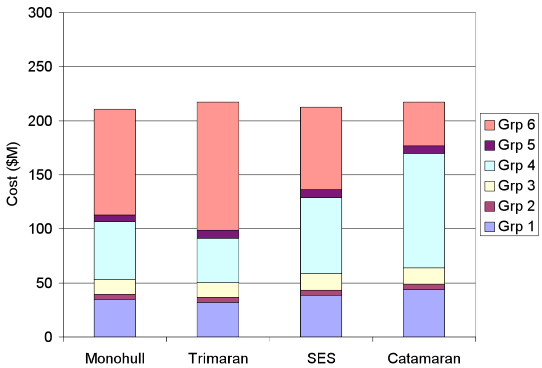

Figure 8: LCS Threshold Performance Cost Breakdown

The hullform with the clearest improvement is the catamaran, with a reduction of approximately $50m for solutions with an equivalent combat system capability. The principle reason for the large reduction in cost of the catamaran solution can be found in Figures 9 and 10. By reducing the requirement for a sprint speed of 50kts with a range of 1500nm to 40kts and 1000nm the catamaran fuel requirement is halved.

The SES solution benefited from a saving of $20m in cost in response to the reduction of performance goals. Figures 9 and 10 give some indication as to why the SES failed to benefit from the reduction in performance requirement to the same extent as the catamaran. For the SES the fuel required for sprint speed does not drive the design, rather the fuel for the 18-24kts speed range with a range of 4300nm proves to be the decisive factor. As the required performance was reduced to 16-22kts with a range of 3500nm the SES does not benefit greatly due to its speed-range profile.

The monohull and trimaran both achieve a cost reduction in the region of $10m. In relative terms the reduction in machinery fit and fuel requirements are smaller than the catamaran, as a consequence the absolute reduction is modest by comparison.

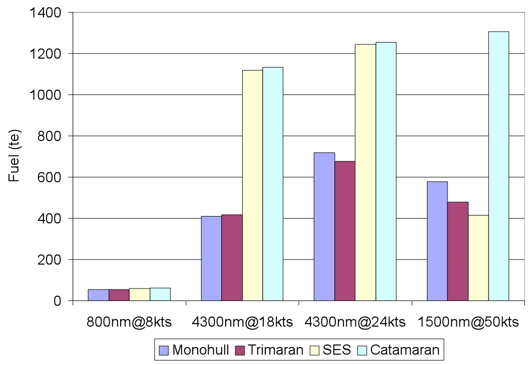

Figure 9: LCS Objective Fuel Usage

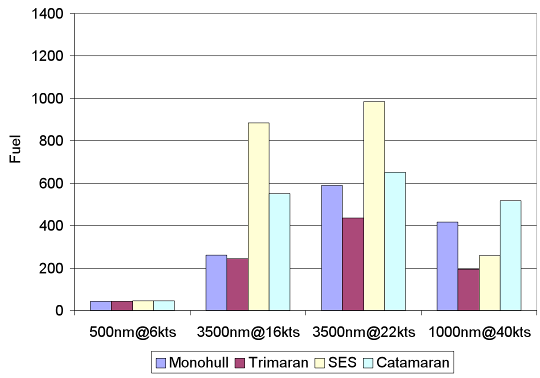

Figure 10: LCS Threshold Fuel Usages

4.3 STRUCTURAL WEIGHT MINIMISATION

Taking the objective balanced designs the effect of reducing structural weight by a factor of 25% was examined. These results can be found in Table 3. The method of costing the structure was not changed in this preliminary investigation and would require further study.

	Reduction in cost	Reduction in weight
Monohull	0.90%	1.40%
Trimaran	2.50%	7.80%
SES	3.90%	12.10%
Catamaran	7.10%	14.80%

Table 3: Impact of reduction in structural weight

The SES and catamaran benefit most from reduction to the structural weight. The large change in both the overall displacement and cost reinforces why most catamaran fast ferries are constructed from aluminium.

5. POINT DESIGNS

This Section develops the designs produced by the earlier method by preliminary feasibility studies. This was done to highlight any issues concerning the validity of the numerically balanced ships presented in Section 4. A simple layout was developed to ensure sufficient space was available for the propulsion systems and other key equipment.

Each of the four hullforms, described in Table 4, considered and evaluated with respect to the principle areas of the study. These designs attempt to demonstrate how the hullforms scale and the issues that are present within small or large vessels of a given hullform.

Hullform	Payload Groups						Price Level ($M)	Relative Capability	Deep Disp. (tonnes)
	SW	AD	SS	IS	MOD	AR			
Trimaran	0	0	1	3	2	1	224	2675	2621.8
Monohull	2	3	3	4	2	1	226.6	3800	2534.5
SES	0	0	1	3	2	1	224.2	2675	3734.4
Catamaran (objective)	0	0	1	0	2	1	230	1445	3028

Table 4: Point designs considered

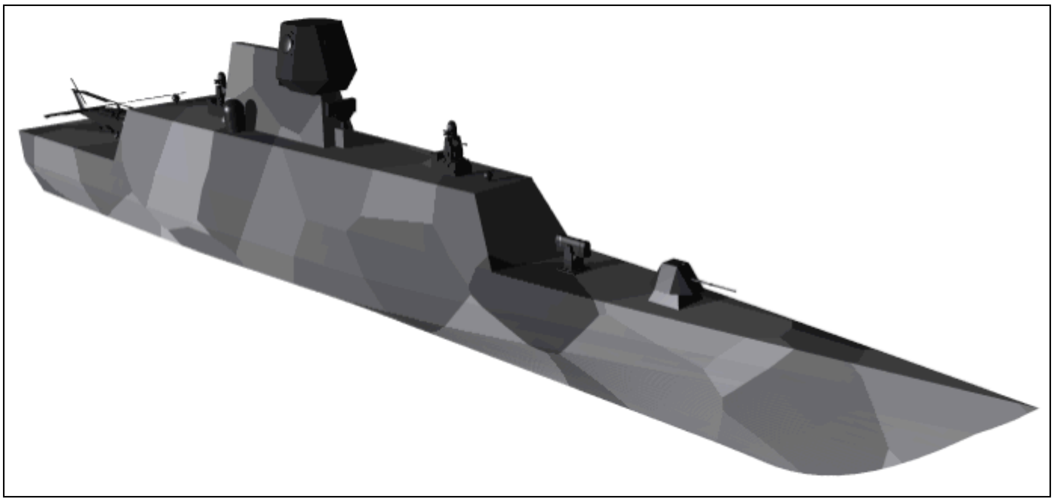

Figure 11: LCS Monohull

5.1 MONOHULL (Figures 11 & 16)

The monohull has been designed to the objective requirements and the target cost, the cost-benefit method suggested the following combination of systems.(Table 5)

SW(2)	76mm 2 x 40mm
AD(2)	RAM 2 x CIWS Nulka
SS(1)	Active sonar Anecheoic tiles Depth charges
IS(4)	CEC Rx & Tx full sensor suite
MOD(2)	4 x Large modular payload bay
AR(1)	Two helicopters

Table 5: Monohull Payload

The major items of propulsion machinery are summarised below.

- Boost power
    - 2 x MT50 gas turbines mechanically driving two 44Mw waterjets
- Integrated Electrical Propulsion
    - Allison 601-k11 (8.3 MW)
    - Allison AG9140 (3.0MW)
    - 2 x Eurodyne (2.4MW)
    - 2 x Retractable Podded Propulsers

The monohull designs all feature a full width superstructure which houses the vessels modular payload package. Below deck areas provide space for the propulsion system and accommodation. One downside of the monohull hullform is the relatively small hanger and flight deck and the issues of access around it.

The main problem with the design of a monohull to the requirements specified is the ability to layout the machinery, particularly with reference to getting the power 'out the back'. The only practical solution was to place the main propulsors, two waterjets, together in the aft compartment.

The machinery choice resulted in two large gas turbines being placed within a relatively narrow hull. As would be expected this caused layout problems, making it necessary to separate the two gas turbines into adjacent compartments. Whilst improving survivability this has however led to long shaft lines that could experience vibration problems.

The method used to select gas turbines alternators chose an Allison AG9140 (3.0MW) and two Eurodyne (2.4MW) gas turbines for the monohull. This is a result of the necessity, within the model, to meet the diverse power requirement of the four operating speeds efficiently. It is recognised that if this concept was developed further the benefits of identical gas turbines from a maintenance and stores perspective would lead to a small power, and hence speed, trade off.

Flush mounted azumizing pump-jets were explored as a suitable low to medium speed propulsor. However, some doubt as to the ability to operate up to LCS's medium speed range resulted in retractable podded propulsors being chosen as the low to medium speed propulsor.

Structurally the monohull is driven by longitudinal bending. Whilst this is well within the knowledge base of current naval ship design there are some unique challenges. The loading on the hull at high speed in high sea states is difficult to predict and further work is required in this area. Due to the requirements for hanger a modular payload space a full width superstructure has been used. Care will be required in the detailed structural design to ensure the large open hanger and modular bays are suitably integrated with the main hull.

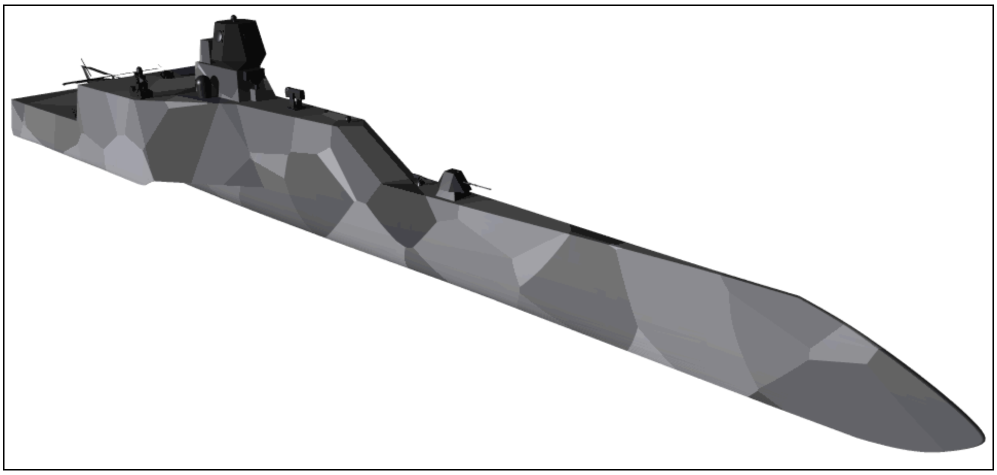

Figure 12: LCS Trimaran

5.2 TRIMARAN (Figure 12 & 17)

The trimaran has also been designed to the objective requirement. The cost-benefit method suggested the combination of systems listed in Table 6. Comparing the payload to that of the monohull it can be seen that the saving in propulsion machinery translate into a second Rolling Airframe Missile (RAM) system.

SW(2)	76mm 2 x 40mm
AD(3)	2 x RAM 2 x CIWS Nulka
SS(1)	Active sonar Anecheoic tiles Depth charges
IS(4)	CEC Rx & Tx full sensor suite
MOD(2)	4 x Large modular payload bay
AR(1)	Two helicopters

Table 6: Trimaran Payload

Powering for the trimaran is provided via the following systems:

- Boost power
  - 2 x LM2500+ gas turbines mechanically driving a single 55Mw waterjet
  - Electrically driven waterjets
- Integrated Electrical Propulsion
  - Allison 601-k11 (8.3 MW)
  - Allison AG9140 (3.0MW)
  - 2 x Eurodyne (2.4MW)
  - 2 x Low speed Pump-jets

The trimaran's large deck area allows the provision of a large space for operating helicopters and UAV's. This large open space is carried forward to the hangar which incorporates enough deck area for two helicopters, whilst allowing ample room for module bays outboard, port and starboard.

As noted above the trimaran uses a combination of a direct drive waterjet in the centrehull, together with electrical motor driven waterjets in the side hulls and pump-jets for manoeuvring. The operating conditions can be divided into three regions: at the top speed the direct drive water jet are used in the centre hull with electrically driven side hull waterjets; medium speeds use only the side hull waterjets driven through the IEP system with an appropriate combination of gas turbine alternators on-line; for low speeds the pump-jets are driven through the IEP system. As with the monohull there is a need to revise the gas turbine selection in light of maintenance and stores concerns.

By locating the smaller set of waterjets in the side hulls the slenderness of the main hull can be retained. However, a major perceived problem with this arrangement is the potential for air ingestion in side hull mounted waterjets at small angles of roll. This issue can be resolved by incorporating scoops into the waterjet intakes. [8]

The requirement for a large modular mission space led to a desire to create a payload bay in the crossdeck/box that links the centre and side hulls. Unfortunately structural issues have been exposed as a possible problem with this space.

The trimaran's structural design is principally driven by longitudinal bending with some transverse loading. If the centre hull side shell is not continued from the cross deck to the upper deck then there is potential for longditudinal bending problems in the region of the box. Pillars would provide an ideal solution to this issue for a merchant ship, however it was felt that their response to shock loading would be unacceptable for a naval vessel. A space frame style structure may be one solution however this would break up the deck area in a similar manner to the side shell, while not providing the inherent benefits of fire and flood protection. The final solution was to create two payload bays either side of the centre hull. The boost gas turbine engines, which exhaust over the stern as proposed in [9], are located in the centre hull between these two bays. These uncertainties have highlighted the potential need for a radical structural configuration for the trimaran in response to internal space requirements. Further work is required in this area to fully define the limits of novel structural requirements.

With the crossdeck being close to the waterline the wet deck clearance is relatively small in comparison to other trimarans[10]. A high wet deck is a common design feature of trimarans in order to minimise slamming and some speed/sea state limitations may need to be imposed with this configuration. Further work is necessary to evaluate the impact of this design choice.

One potential novel load in this design could arise from the side hull propulsers, two waterjets rated at 4Mw each. There is however some precedent for side hull propulsers, with two 350KW side hull thrusters installed in RV Triton [10]. The results of her trial program may provide some insight as to the impact of this arrangement.

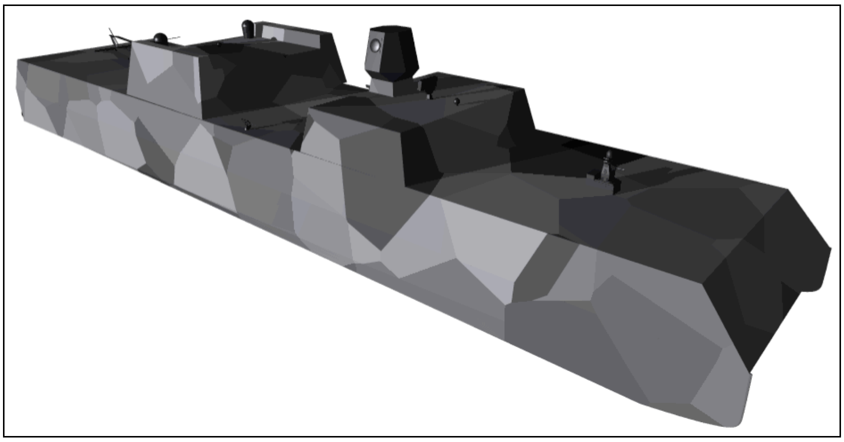

Figure 13: LCS SES

5.3 SES (Figures 13 & 18)

The surface effect ship is also designed to the objective requirement. The cost-benefit method suggested the combination of systems summarised in Table 7.

SW(0)	2 x 20mm
AD(0)	CIWS
SS(1)	Active sonar Anecheoic tiles Depth charges
IS(4)	CEC Rx & Tx full sensor suite
MOD(2)	4 x Large modular payload bay
AR(1)	Two helicopters

Table 7: SES Payload

- Prime movers
  - 2 x WR-21 mechanically driving two waterjets
  - 3 x Eurodyne (2.4MW)
  - 4 x Pumpjets
- Lift System
  - 4 x LM500 to 4 lift fans

The large open box of the SES provides more than enough scope for novel machinery layout options. Efforts have been made to distribute the redundant key items, such as prime movers, throughout the ship whilst concentrating systems with no redundancy, such as the radar and control room.

A conscious decision was made to integrate the module handling system with the hangar. By having it running to the stern of the ship beneath the flight deck the payload bay can deploy and retrieve ROV's or small boats from the stern. These operations may potentially be limited by both speed and sea state and further work is necessary in these areas.

Access is also provided via the stern for larger objects allowing the payload bay to operate as a small ro-ro deck. Boat bays, positioned along the sides of the ship, would offer other access point to the payload bay if stern docking was not feasible for a given port.

SES machinery selection was driven by the requirement for a light weight solution. Lift fans driven by electrical motors were investigated, but efficiency gains made possible by operating generators at full power were insufficient to counteract the substantial weight penalties.

As with the trimaran side hulls the shallow operating draft when on cushion poses a problems with potential air ingestion into the waterjets, it is felt that this can be resolved by scoops but with the penalty of increased resistance. [8]

The requirement for a large range at speeds in the region of 18-25 knots proved decisive in limiting the effectiveness of the SES. This is a region where cruise speed fuel consumption drives up the fuel requirement of the SES and hence displacement. It is present while either off cushion (with the prime movers at full power and lift fans off) or on cushion (with the prime movers at part load and lift fan gas turbines running). (Figure 14)

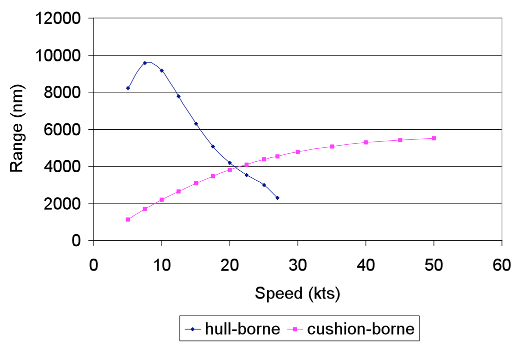

Figure 14: SES speed-range curve for a fixed fuel load

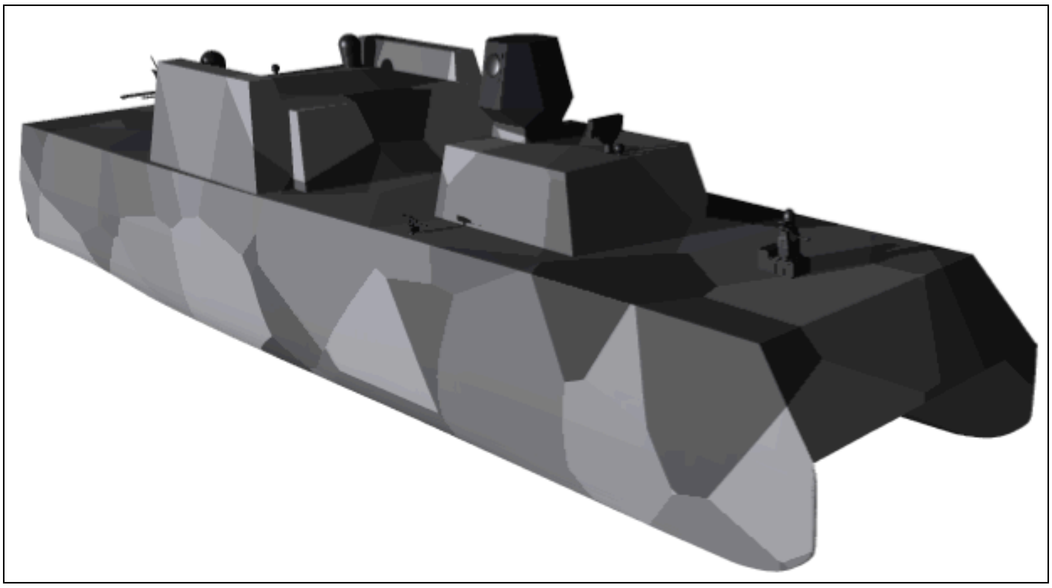

Figure 15: LCS Catamaran

Finally the SES design has a high length to beam ratio. Whilst this has been shown to be beneficial for the SES powering, it can however lead to problems with stability during high speed turns.[8][11]

Unlike the catamaran the hulls are not optimised for hydrodynamic performance but are a compromise and must accommodate the on cushion design requirements including the operation of the skirts.

5.4 CATAMARAN (Figure 15 & 19)

Unlike the three previous hullforms the catamaran was only designed to the threshold performance requirements, because as described earlier (see section 4.1) the cost of designing the catamaran to the objective performance requirements was far in excess of the target cost.

Cost-benefit method suggested the following combination of systems.(Table 8)

SW(0)	2 x 20mm
AD(0)	CIWS
SS(1)	Active sonar Anecheoic tiles Depth charges
IS(0)	CEC Rx
MOD(2)	4 x Large modular payload bay
AR(1)	Two helicopters

Table 8: Catamaran Payload

- Boost power (40kts)
    - 2 x MT-50 gas turbines mechanically driving two 43Mw waterjets
- Integrated Electrical Propulsion
    - WR-21 GTA (21.0 MW)
    - Allison 601-k11 (8.3 MW)
    - Eurodyne (2.4MW)
    - 2 x Electrically driven waterjets
    - 4 x Pumpjets

Many of the catamaran's advantages are equivalent to those described for the SES. The large structural box allowed the integration of the module handling system with the hanger. It also runs to the aft of the ship allowing the deployment and retrieval of ROV's or small boats over the stern.

Power requirements for the catamaran were found to be large compared to the monohull and trimaran, this assessment is supported in [12]. The impact of this difference in required power becomes apparent when the 40 knot catamaran is compared to the 50 knot monohull. In both cases the sprint propulsion is provided by two MT-50 gas turbines driving two 40Mw waterjets.

The beam of the two hulls is only just sufficient to fit in the waterjets. Any further increases led to increased resistance, causing the ships displacement to spiral up. Gas turbines however were far too large due to access requirements. They have been placed in the box, either side of the hangar, leading to long shaft lines that could experience vibration problems. An electrical drive configuration was explored to attempt to resolve these layout constraints but the weight penalties of a 100+Mw IEP system were severe.

The final displacement for the threshold level catamaran is comparable with that of the Stenna HSS. On this basis the catamaran concept could be regarded as being partially derisked. However publicly available detailed studies of the design and performance of the large catamarans are limited, especially those written from a naval perspective.

5.5 HULLFORM COMPARISON

Summarising the previous discussion the monohull could be described as the most low risk hullform. This could be an important factor as no allowances have been made in the costing process for novelty.

If the buyer is willing to accept some risk the trimaran offers the best capability of any cost level. The powering benefits of the trimaran in the LCS role are clear and have allowed the solution to advance clearly in comparison with the other designs.

The catamaran and SES both suffered from the payload choices which led to the final solution weight spiralling upwards. If the payload was composed of lightweight space hungry items (i.e. UAV's) then the twin hulled solutions may offer substantial benefits.

Also in the case of the SES a change in the mission profile towards the higher speed regions would make this hullform far more competitive. The top speed of fifty knots is slightly too low for the high speed benefits of the SES to shine though. Conversely if the top speed requirement is relaxed the benefits of the trimaran over the monohull reduce. Other factors could also skew the order of merit, for example if importance of mine countermeasure operations were increase then the SES could gain favour due to its ability to operate on an air cushion.

6. CONCLUSIONS

As stated in Section 4 the trimaran is the most effective hullform for the task given the current operation requirements, allowing the maximisation of payload capability over the range of payload options considered. Next is the monohull, then the SES and finally the catamaran. The order is identical for the objective and threshold performance requirements, however there is a substantial change in the relative payload capability of the hullforms as the performance requirements are changed. Should the operational requirements alter this order could change.

The results clearly demonstrate that the reduction of the performance requirements gives rise to an increase in the capability achievable, for a given cost. This effect can be seen to be very pronounced for the catamaran, with a speed reduction of 10 knots saving approximately \$50m.

While the combat system is a major component of a warships cost, this study has shown that the choice between different platform types can have considerable impacts on overall capability. The work has highlighted the necessity to examine different hullforms in the early stage of the concept design process.

6.1. ABILITY TO PREDICT PERFORMANCE

Powering predictions for the LCS were always challenging considering the high speeds of the ships. This work has highlighted the lack of accurate ship resistance predictions able extend to the speeds of the LCS.

Potential speed/sea state limitations for the various configurations were not determined due to a lack of appropriate tools.

Accurate prediction of the structural weight was hard due to the large variation in the loading conditions of the hullforms. There is a real lack of guidance, especially in terms of early stage design, for structural weight prediction for multihull craft.

The current generation of performance prediction tools for resistance, seakeeping and structural design all require highly detailed ship definitions. There is a requirement for a set of performance analysis tools more suited to initial design when less is known about the ship. Ideally tools should be produced that give results for a large range of possible ships types and sizes, together with a confidence level for predictions, particularly in the areas of:

- Structures
- Seakeeping
- Powering

If, as suggested by [13], over 70% of cost of a warship is locked in during the early design stage then selection of an appropriate hullform must play a key role. However for any hullform selection process to be truly representative tools must be available to evaluate the candidate designs.

7. ACKNOWLEDGEMENTS

This work was supported by The Atlantic Center for the Innovative Design and Control of Small Ships under the auspices of the United States Office of Naval Research - BAA No: 02-019. The support of Mr. L. Ferreiro at the London office of Office of Naval Research is also recognised. Finally the effort of MSc and MEng students from UCL who developed LCS designs upon which this work is derived is recognised: Lt Cdr Boyle, RN, Lt Gulatti, CF and Mr Newman for developing the trimaran concept design; Lt Unnikrishnan, IN, Lt Rawson, RN and Lt Goodall, RN for developing the SES design; and Lt Ali, PN and Lt Watkins, RN for developing the monohull design.

8. REFERENCES

[1] CEBROWSKI A.K. and HUGHES W.P.. 'Rebalancing the fleet' *U.S. Naval Institute Proceedings*, pages pp. 31–34, November 1999.

[2] JAFFE, G. 'Debate surrounding small ship poses fundamental questions for us navy.' *Wall Street Journal*, July 11, 2001.

[3] 'Preliminary design interim requirement document for littoral combat ship (LCS) flight 0' Technical report, US Navy, 2003.

[4] GREIG, A., BUCKNALL, R. and GRAFTON, T. (2003). 'Fast trimaran corvette' NATO Advanced Vehicle Technology symposium on Vehicle Propulsion Integration, Warsaw, Poland 6-9 Oct 2003. 12 pages. [in print]

[5] HOLTROP, J. and MENNEN, G.G.J. A. '"An Approximate Power Prediction Method" International Shipbuilding Progress, Vol. 29, No. 235, July 1982.

[6] MERCIER, J.A. and SAVITSKY, D. 'Resistance of Transom-stern Craft In The Pre-Planing Regime', Technical Report, Davidson Laboratory, 1973

[7] HUBBLE, E.N. 'Resistance of Hard-chine, Stepless Planning Craft with Systematic Variation of Hull Form, Londitudinal Center of Gravity and Loading', Navy Research and Development Center, 1974

[8] BUTLER, A.B. 'The Surface Effect Ship', Modern Ships and Craft, Naval Engineers Journal, Vol 97, No.2, 1985.

[9] NEWMAN,T 'Trimaran littoral combat ship - naval architects report' Technical report, Ship Design Report, 2003.

[10] PATTISON, N. and SEARLE, G. 'The Design and Construction of RV Trition – The Trimaran Demonstrator', RV Triton: Trimaran Demonstrator Project, RINA, 2000

[11] YUN, L and BLIAULT, A. 'Theory and Design of Air Cushion Craft', Arnold, UK, 2000.

[12] SADDEN, J.A. and NISBET, C 'Are two hulls better than one (or three)? Warship '98, RINA, 1998.

[13] TIBBITS, B. and KEANE, R. 'Making Design Everybody's Job; The Warship Design Process', Naval Engineers Journal, Vol 107, No.3 1985

9. AUTHORS BIOGRAPHY

Tim McDonald joined University College London as a research assistant in 2000. He is currently undertaking research for his PhD which addresses the feasibility of multi-vehicle type Concept Design procedures, methodologies and tools. A large element of his work at UCL is providing support for the undergraduate and postgraduate ship design exercises at UCL.

Simon Rusling has divided his career between defence project management with the Royal Corps of Naval Constructors (RCNC) and two secondments to UCL, including his current appointment as Professor of Naval Architecture. His defence project management experience has covered all aspects from research, through concept formulation, detailed design and build to in-service support. At UCL he is responsible for the undergraduate and postgraduate courses in Naval Architecture.

Alistair Greig was trained as a Marine Engineer by the UK MoD (RCNC) spending time as sea on warships and submarines. His BSc Mechanical Engineering and MSc Marine Engineering were completed at University College London (UCL). He subsequentaly studied for a part time PhD at UCL in the application of robotics under water. Appointed as a lecturer in the Department of Mechanical Engineering at UCL in 1989 and then a Senior Lecturer in 2001.

Richard Bucknall began his career as a student engineering apprentice with the BP Shipping Company. After graduating with an honours degree in Electrical and Electronic Engineering and having gained his Certificates of Competency with some 24 months seatime he left the merchant navy to pursue an academic career ashore. He joined the staff of the Royal Naval Engineering College gaining a PhD and was elected College Research Fellow. He joined the staff at University College London in 1995 and he is currently the Director of the Marine Engineering MSc Course. His research interests are diverse and include electrical ship technologies and offshore electrical engineering activities.

Category	Threshold Level	Objective Level
Total Price per Ship	Meet CAIV target in the REP	Exceed CAIV target in the REP
Hull Service Life	20 Years	30 Years
Draft at Full load Displacement	20 feet	10 feet
Sprint	1000 nautical miles at 40 Knots	1500 nautical miles at 50 Knots
Naval strike	3500 nautical miles at 22 Knots	4300 nautical miles at 24 Knots
Fleet operations	3500 nautical miles at 16 Knots	4300 nautical miles at 18 Knots
Anti-submarine warfare	500 nautical miles at 6 Knots	800 nautical miles at 8 Knots
Aviation Support	Embark and hangar: one MH-60R/S and VTUAVs, and a flight deck capable of operating, fueling, reconfiguring, and supporting MH-60R/S/UAVsNTUAVs	Embark and hangar: one MH-60R/S and VTUAVs, and a flight deck capable of operating, fueling, reconfiguring, and supporting MH-60R/S/UAVsNTUAV
Aircraft Launch/Recover Sea State	Sea State 4 best heading	Sea State 5 best heading
Watercraft Launch/Recover	Sea State 3 best heading with in 45 - mins.	Sea State 4 best heading with in 15 - mins.
Mission Package Boat type	11 Meter RHIB	40 ft High Speed Boat
Time for Mission Package Change-Out to full operational capability including system OPTEST	4 days	1 days
Provisions	336 hours (14 days)	504 hours (21 days)
Underway Replenishment Modes (UNREP)	CONREP VERTREP and RAS	CONREP VERTREP and RAS
Mission Module Payload (note 3)	180 MT (105 MT mission package / 75 MT mission package fuel)	210 MT (130 MT mission package / 80 MT mission package fuel)
Core Crew Size	50 Core Crew Members	15 Core Crew Members
Crew Accommodations (both core crew and mission package detachments)	75 personnel	75 personnel
Operational Availability (Ao)	0.85	0.95

Table 9: LCS Flight0 Critical Design Parameters, adapted from [3]

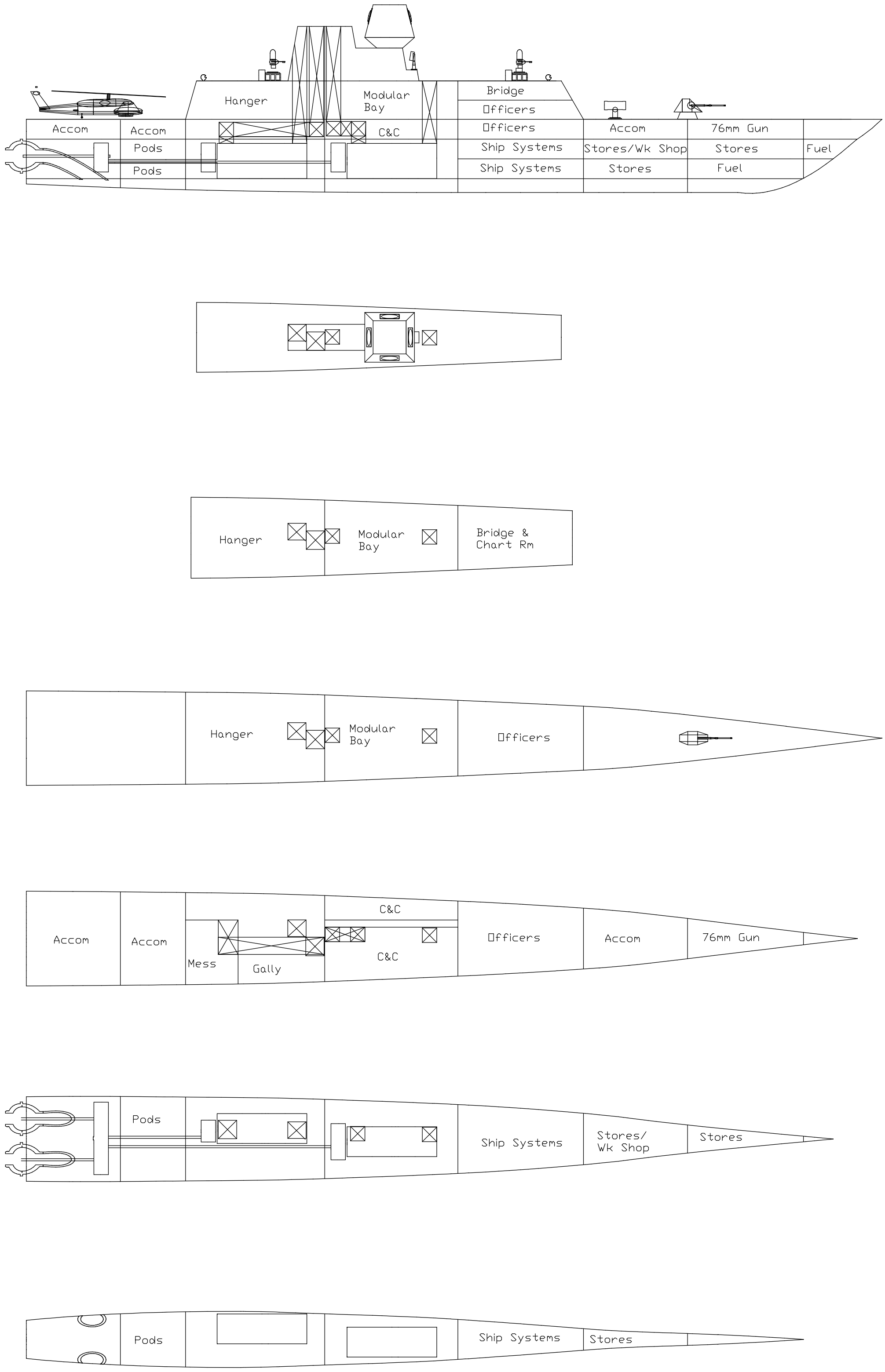

Figure 16: Monohull General Arrangement

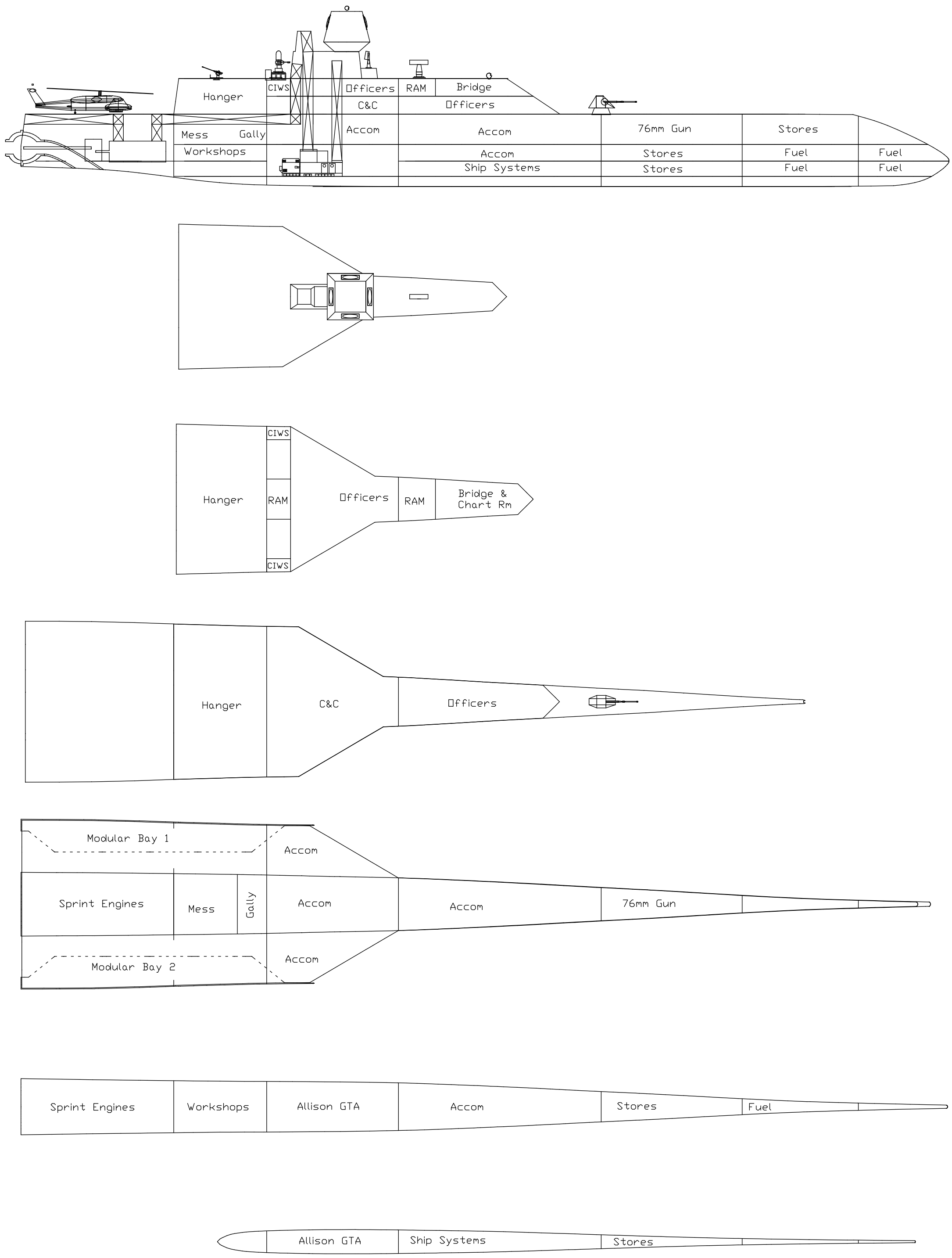

Figure 17: Trimaran General Arrangement

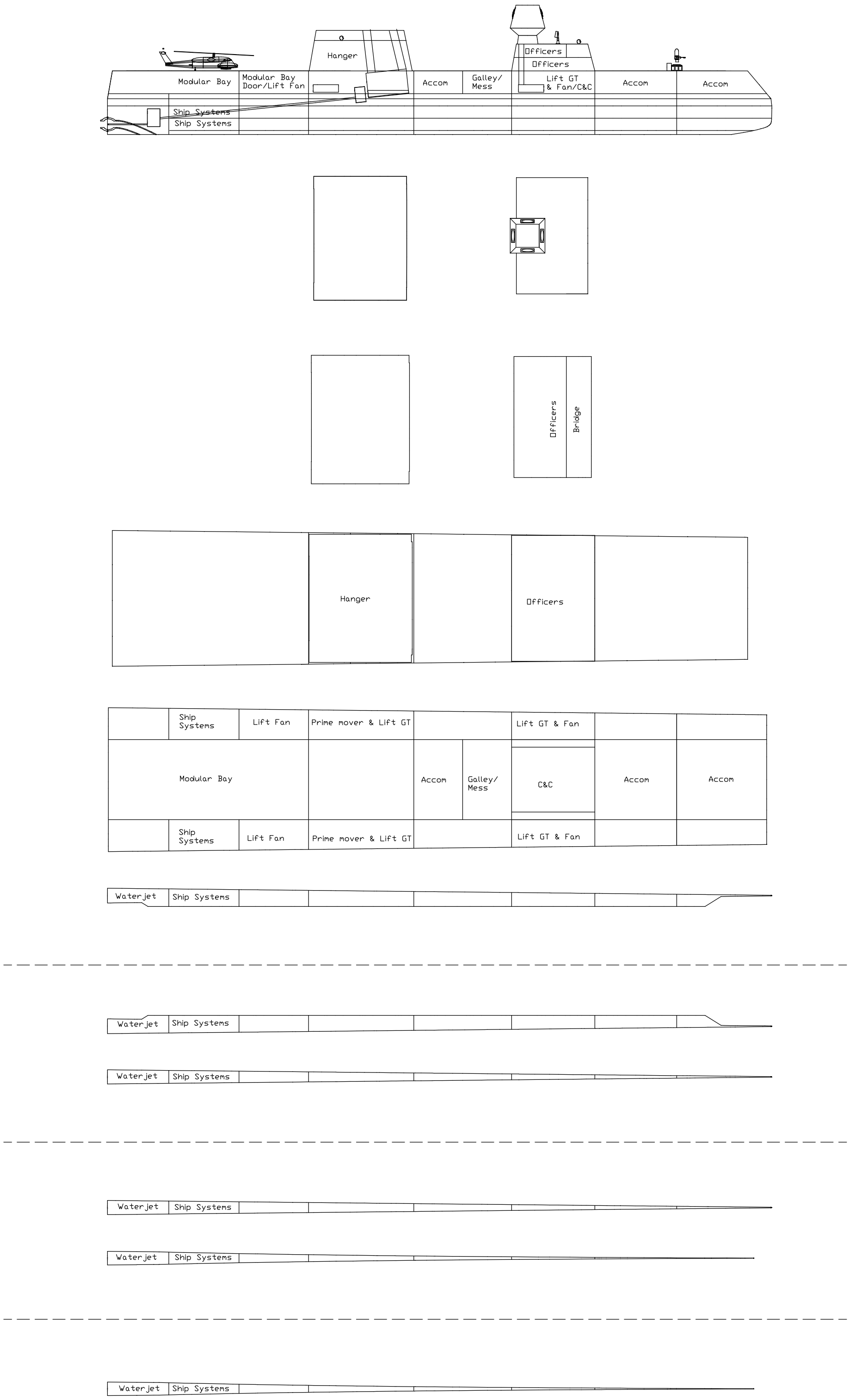

Figure 18: SES General Arrangement

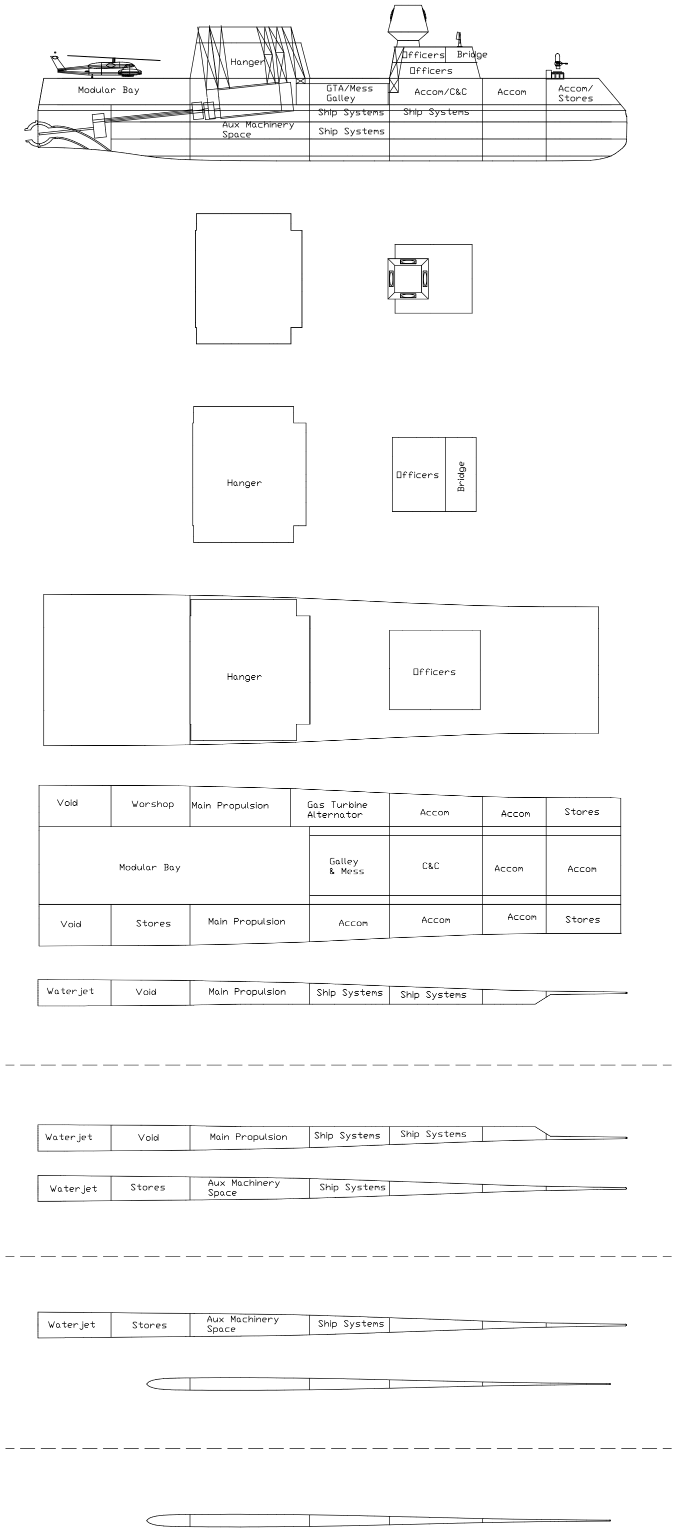

Figure 19: Catamaran General Arrangement

Appendix B

Concepts for a Fleet Tanker: An Exploration into Options and Pricing

This appendix was published as a conference paper entitled "Concepts for a Fleet Tanker: An Exploration into Options and Pricing" in the Royal Institution of Naval Architect's Conference on Military Support Ships in London, April 2007.

CONCEPTS FOR A FLEET TANKER: AN EXPLORATION INTO OPTIONS AND PRICING

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D P G Burger, Graphics Research Corporation, UK
T P McDonald, University College London, UK

SUMMARY

The UK Ministry of Defence (MoD) is replacing the majority of its naval auxiliary ships. The immediate requirement is to procure up to six Fleet Tankers that are compliant with IMO double-hull requirements. The Fleet Tanker requirements are fundamentally commercial in nature, but with several additional specific military features. Achieving a balance between commercial and naval requirements is a current challenge for the MoD, and understanding the associated costs is essential in that trade-off. To this end, a systems engineering approach was taken to establish a series of designs corresponding to different requirements and to estimate the costs of the changes. By widening competition to commercial shipyards, and keeping specifications essentially "commercial" in nature, the UK hopes to procure tankers at a "commercial" price.

NOMENCLATURE

MoD	Ministry of Defence, United Kingdom
AO	Auxiliary Oiler
RFA	Royal Fleet Auxiliary
IMO	International Maritime Organisation
RAS	Replenishment at Sea
RAS(L)	Replenishment at Sea for Bulk Liquids
CVF	Future Aircraft Carrier (UK)
C_b	Block Coefficient
C_m	Midships Section Coefficient
B_{wl}	Beam at Waterline (m)
T	Draught (m)
D	Hull Depth (m)
θ	Angle of Flare at Waterline (rad)
r	Bilge Radius (m)
p	Shipbuilder's Profit Margin (%)
P_{ship}	Price of Ship (£)
CER_M	Material Cost Estimating Ratio (£/t)
CER_L	Labour Cost Estimating Ratio (hrs/t)
WT_i	Weight of Group i (t)
HR	Shipyard Average Hourly Rate (£/hr)
CL	Cost of Labour (£)
CM	Cost of Materials (£)
LC	Learning Curve (%)

1 INTRODUCTION

The UK Ministry of Defence (MoD) is planning to replace several tankers, which make up a large proportion of the Royal Fleet Auxiliary's (RFA) logistics support flotilla. The new ships, known as the Fleet Tankers, in combination with additional auxiliary support ships, will be critical to the Royal Navy's ability to conduct worldwide operations while minimising dependency of UK joint forces deployments on host nation support.

1.1 MISSION

The requirement for new tankers arises not only from ships reaching the end of their life, but from the UK's stated commitment to satisfy IMO regulations requiring that all tankers feature liquid cargo protection by means of a double-hull. As single-hull tankers are phased out and flag state authorities start to require compliance in order to gain port access, non-compliance with IMO regulations may have implications in terms of global reach. While the Fleet Tanker design can essentially mimic that of a commercial oil tanker, there are several mission areas, described below, which require upgrades or the addition of military features.

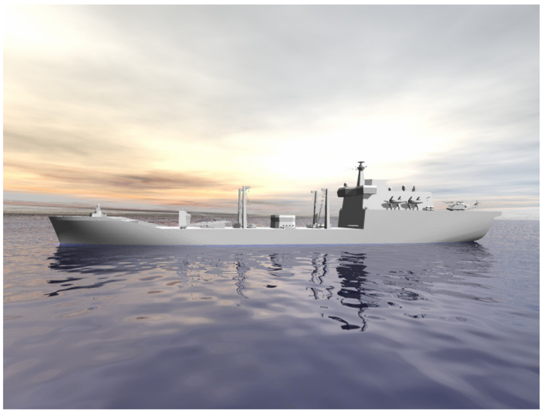


Figure 1: Computer Generated Image of a Fleet Tanker

The primary role of the proposed Fleet Tanker Class is to deliver bulk fluids such as Marine Gas Oil, Aviation Kerosene, Single Battlefield Fuel, and Potable Water, to Naval Task Groups (including CVF), Naval Combatants, and other Auxiliary ships. Typically, transfer takes place by abeam replenishment via the delivering ship's RAS(L) rig. Other methods will be utilised, however, for different replenishment situations and sea-states, such as astern refuelling or over the bow transfer to a single point mooring buoy.

A further possible role of the Fleet Tankers is to provide aviation support to naval warships or an amphibious task group. Corresponding aviation facilities, such as a flight deck, hangar, refuelling equipment, air weapons magazine, aircraft maintenance facilities, and accommodation for associated personnel may therefore play a large part in differentiating the overall size and design of the Fleet Tanker Class from commercial tankers of equivalent cargo capacity. This capability is seen as a large driver of ship cost, and this paper considers its relative contribution to the ship's procurement price.

Ship mobility is another area where the Fleet Tanker design requirements may differ from those of typical commercial shipping. Where most commercial tankers are designed to operate at a fixed transit speed of around 14 knots—with hullform and main machinery design optimised accordingly, a naval auxiliary tanker, on the other hand, has a more complex operating profile with a maximum speed dictated by faster warships with which it may need to keep pace, and a lower loiter speed and a speed at which the ship conducts its RAS operations. For naval and naval auxiliary ships to maintain high fuel efficiency and ship availability, machinery selection becomes increasingly important. To this end, electric propulsion may be demonstrated as being appropriate if it is shown to satisfy the demands of the ships' complex operating profiles.

Despite these possible differences from standard commercial tanker designs, procurement of the new Fleet Tankers is intended to involve the adoption of commercial design and build standards and practices wherever possible. This strategy is intended to open up the competition for the Fleet Tanker contract to shipbuilders who have traditionally dealt mainly with commercial contracts.

1.2 REQUIREMENTS

It is the aspiration of the MoD that the solution for the Fleet Tanker is based on proven commercial concepts. As a "smart customer," that understands the costs implied by requirements, it is the intention to keep the specification as "commercial" in nature as possible to keep the price as "commercial" as possible. The MoD intends to keep changes to the contract to a minimum during the build phase, and in order to keep the specification clear it will be prescriptive in nature. Nonetheless, given the MoD's focus on minimizing ownership costs, for a small number of critical items the MoD may ask the shipbuilder to assess through-life cost to ensure the selection of quality equipment.

2 DESIGN PHILOSOPHY

As shown in Figure 2 below, the basic layout of the Fleet Tankers is a flight deck aft, cargo tanks occupying the majority of the ship's length forward, and an accommodation deckhouse in between. This arrangement, with the exception of the flight deck, is typical of most tankers in service commercially. Main machinery, whether in single or separate compartments, is located aft of the cargo tanks.

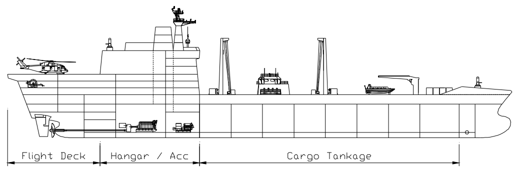


Figure 2: Fleet Tanker size drivers

2.1 CARGO

The cargo carrying capacity of a tanker is the primary factor governing the overall size and length of the ship. Commercial tankers typically find that they can most efficiently transport cargo by adopting a high block coefficient (C_b) and low transit speed (≈14 knots). The Fleet Tankers may operate at higher speeds than commercial tankers, therefore adopting a commercial hullform, optimised for lower speeds and sea-states, may not prove efficient and a longer, finer hullform than a commercial tanker of equal cargo capacity (as well as more power) may be required if speed requirements are significantly higher.

The main cargo oil grades carried by the Fleet Tankers will be loaded and off-loaded through the series of main cargo tanks within the hull. It is common practice for commercial vessels to feature large cargo holds bound by main transverse bulkheads and a single centreline bulkhead. This arrangement provides the loading flexibility required of a commercial vessel where oil cargo is loaded at one port and offloaded at another. Once at the fuel terminal this oil can be filtered to ensure particulates are removed. The Fleet Tankers will have the more onerous requirement of ensuring oil issued to other ships is of adequate quality; therefore, all oil must be filtered before delivery, necessitating either a high volume filtering system capable of filtering oil at pump over rate or a dedicated filtering tanks where processed oil can be contained prior to issue. The decisions made in this area are likely to affect the final tank layout. A centreline issue tank layout with a separate cargo filtration plant, as on AO ships, offers an effective on-board oil filtering and storage arrangement although it has the negative effect of increased steel weight and manufacturing costs.

The Fleet Tanker will be required to operate in multiple loading conditions since it will conduct several partial offloads during a typical operation. This requirement also has a direct bearing on the choice of tank layout, with the aforementioned centreline issue tank arrangement offering a very flexible solution whereby changes in heel can be minimised by processing and offloading oil cargo via the centreline tanks.

Figure 2 illustrates the approximate location of the cargo tanks relative to the aft spaces of the Fleet tanker. Length demands for aviation features have the effect of moving the cargo tank spaces further forward in the ship thereby increasing the magnitude of trim changes—as loading conditions vary, it becomes difficult to keep the ship's centre of gravity close to amidships. An extensive ballast system is required accordingly, and the double-hull, based on IMO guidelines and spanning the length of the cargo holds, is likely to be utilised as a series of double bottom and wing ballast tanks to provide trim compensation in intermediate and light load states.

The choice of cargo pumping system adopted for the Fleet tankers will require careful consideration. The two most commonly used and readily available types are deepwell pumps within each cargo hold, or cargo pumps located in a dedicated pump room between the deckhouse and the cargo holds. In the selection of an appropriate system, all variables must be considered such as affect on ship length, initial procurement cost, survivability, cargo hold layout, and through life reliability, and maintainability.

2.2 FLIGHT DECK AND HANGAR

The addition of an aviation facility on board the Fleet Tankers can provide the capability to operate and maintain rotorcraft of medium to large size, but has a large impact on overall ship size and layout. The minimum feature for an aviation facility is the flight deck. On naval vessels the flight deck is typically placed aft since this is recommended by pilots as being the safest area for helicopters to operate while the ship is underway. In order for the ship to transit with a helicopter onboard for an extended period of time however, a hangar is also required for storing and maintaining the aircraft. Additional spaces may also be needed, such as flight briefing rooms, offices, workshops, air weapons magazines, and air-staff accommodation areas, all of which contribute to overall ship size.

2.3 REPLENISHMENT AT SEA (RAS)

The standard method of performing underway replenishment of bulk liquids, RAS(L), from large supplying ships is via a jackstay fuelling rig. The associated main equipment involved includes a fixed post structure (the rig) integrated with the main structure of the supplying ship, associated winches to control the transfer hose(s) and supporting ropes, and a winch control position with full visibility of the RAS(L) equipment. The position of the Fleet Tanker replenishment rigs will be selected based on the layout of receiving ships such that the location of amidships of both the sending and receiving vessels are as close as possible in order to couple their rolling motions. The placement of these rigs may not, however, drive the length of the tanker due to the abundant deck area available above the cargo tanks, which span the majority of the length of the ship.

Astern refuelling via a stern hose arrangement such as the commonly used Hudson Reel system provides the ability to replenish ships in high sea states while underway, and transfer liquids to ships which do not feature abeam RAS reception equipment. Although not a major ship size driver, an astern reel occupies considerable deck area and height, and a typical quarterdeck is unlikely to provide sufficient free space for the unit. Other, less space demanding methods of astern refuelling are available such as lay-on-deck hoses. The astern refuelling requirement is, therefore, an important consideration in the design of the ship's aft arrangement.

2.4 OPERATIONAL REQUIREMENTS

The Fleet Tanker will be Panama and Suez Canal Authority Compliant and capable of operating within current UK port infrastructure and ports around the world. This leads to constraints on the design of the tankers such as a maximum length of 220m, a maximum beam of 32m, a maximum draught of 11m, and a maximum air draught of 39m in the ballasted condition (to permit passage below the Forth Road Bridge). Compatibility with worldwide oil terminals will be enabled through compliance with relevant commercial shipping legislation and the Oil Companies International Marine Forum (OCIMF), which mandates details such as the position of the cargo manifold. [1]

2.5 SURVIVABILITY

Other than mission systems, survivability is the main feature that differentiates naval ships from commercial equivalents. Unlike speed or cargo capacity, it is difficult to define survivability in terms of ship performance, and this represents a dilemma when it comes to procurement. Many attempts have been made, but these usually involve probabilistic accounting of a set of assumed threats. Analyses like these can be tedious, and are likely to be out of the normal practice of commercial shipyards. Consequently, the MoD intends to use appropriate commercial standards combined with some prescriptive requirements to achieve a suitable level of survivability. For instance, by specifying fatigue limits for structure and identifying essential equipment calling for specific shock mounting, the ship will satisfy shock requirements without requiring a shipyard to have an in depth understanding of MoD shock guidelines.

Since the Fleet Tanker will be classed by Lloyd's Register, it is worth understanding the survivability benefits that are gained by applying guidelines available from class notation, and with which commercial shipyards may be familiar. One such Lloyd's notation is PSMR, which calls for redundancy of essential machinery; or additionally, the longitudinal separation of essential machinery, PSMR* [2]. Eliminating single points of failure in the ship's mobility system would greatly reduce overall vulnerability, but may add to ship cost, for example, longitudinal separation of essential machinery may also have the knock on effect of increasing ship length.

The MoD intends to investigate a range of survivability measures based on the criteria of cost, performance, and applicability to future MoD Auxiliary Ships. Fundamentally, it is the responsibility of the MoD to determine the features that are required to achieve a desired level of survivability, and it is equally important to understand the cost implications of the features specified. Furthermore, specifications will need to be communicated to the shipyard in a clear way to eliminate any possible misinterpretation and to minimise the risk for the shipbuilder.

3 DESIGN PROCESS

In order to compare a wide range of designs and options, a process was developed to ensure consistency across the series. In addition, variations in the design needed to be rapidly assessed. The model developed uses a systems engineering approach.

3.1 SYSTEMS ENGINEERING

Systems engineering is an iterative process. It begins with requirements as inputs, and designs are refined and assessed until all requirements are satisfied. Applied to the Fleet Tanker design, requirements are fed into functional areas, depicted in the flowchart below in Figure 3, all of which are dependent on calculations from each other. Calculations are repeated iteratively until the answers converge on a single solution. Cost and performance of the converged solution can then be assessed as an output of the process. Effectively, the process by which the ship designs are done needs to be fully laid out before the designs themselves are begun.

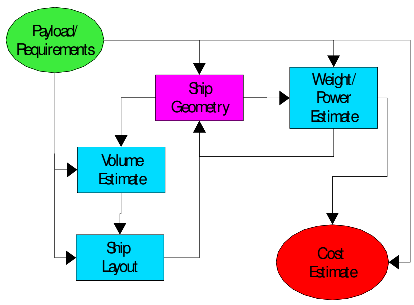


Figure 3: Systems engineering process applied to Fleet Tanker design

Mainly, the purpose of the synthesis process is to ensure that everything fits into a feasible hullform, the weight and buoyancy match, and there is enough volume and length available in the hull and superstructure to meet the requirements. The process is accomplished rapidly using the iteration feature of Microsoft Excel, and all calculations are done within Excel spreadsheets with the exception of the hull geometry, which is calculated in the naval architecture, design, and analysis package Paramarine.

In order to create this design loop integration, a link between Excel and Paramarine was provided to the MoD by the makers of Paramarine, Graphics Research Corporation Ltd. (GRC). This allows geometric calculations related to the hullform and specific functional spaces to be seamlessly integrated with spreadsheet based calculations such as weight and cost estimating.

3.2 PARAMETRIC HULLFORM

Many ship design methods describe aspects of vessel geometry using empirical relationships, i.e. estimating hull volume available. Advances in naval architecture design and analysis tools however, have allowed many of these ship characteristics to be assessed earlier in the design process. As described previously, this study attempts to understand the ship's geometry, in particular, hullform shape, concurrently with other aspects of the design. To assess these characteristics, however, a hullform must be developed, yet generating a fair, well proportioned hullform is far from trivial.

Paramarine is employed by the MoD to undertake design and analysis work and was used to generate the hullform. A number of different hullform generation methods are currently available in Paramarine:

- Manual Surface Manipulation
- Quickhull
- Intellihull
- X-Topology (under development) [3]

The Fleet Tanker will resemble a merchant ship style hullform (with considerable parallel midbody, flat of bottom/side and possibly a bulbous bow). From the Paramarine hullform generation methods listed above, Intellihull is most suited to the parametric generation of merchant ship hullforms.

Intellihull uses a set of 3D curves, termed guide curves, to define the shape of key areas of the hullform. The guide curves are used to control the shape of the bow, the parallel midbody and the transom. Intellihull is able to distort these curves to attempt to match a range of demands input by the designer (i.e. displacement, C_b, or waterline length). However, to ensure the hullform is fair and achieves the demands, the designer must modify the guide curves and demands iteratively. For this study a more reliable parametric approach was required to integrate the generation of ship geometry into the overall design tool.

A set of parametrically controlled guide curves were developed to form the basis of the Intellihull hullform. Considering, as an example, the guide curve at amidships; the following variables were treated as inputs: midships coefficient (C_m), waterline beam (B_{wl}), draught (T), and angle of flare at the waterline (θ, defined in radians), as shown in Figure 4.

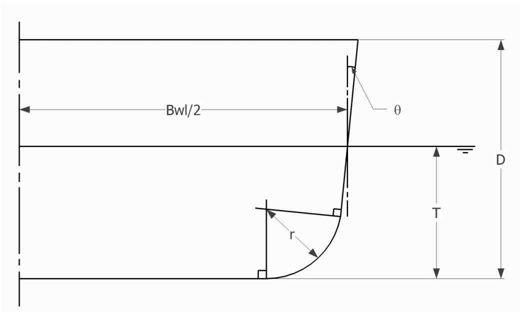


Figure 4: Half Midships Section of Merchant Hullform

By definition,

$$C_m B_{wl} T = \text{Immersed Midship Area}$$

Equation 1

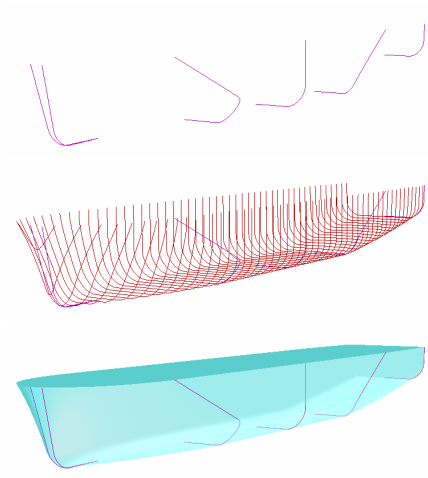
However, the amidships area can also be determined geometrically from B_{wl}, T, θ and the bilge radius (r). Algebraic manipulation then gives an equation for the bilge radius in terms of the input variables.

$$r = \sqrt{\frac{4C_m B_{wl} T - 4B_{wl} T + 2T^2 \tan\theta}{\pi - 2\theta - 4\sec\theta + 4\tan\theta}}$$

Equation 2

Solving this equation fully defines the shape at amidships. This shape can then be described within Intellihull by defining guide curve points and the shape the curve takes between these points (either straight or curved). Similar relationships were developed to define the remaining guide curves.

The inputs to these relationships and the order in which they are evaluated were informed by the flow of information through the systems engineering process described herein. Other elements of the tool, such as the weight and volume sizing, provided values for key input variables such as displaced volume, waterline length, C_m, extent of parallel midbody, beam to draught ratio, and the angle of flare at amidships (θ). Using these relationships and inputs, a model was developed to ensure all numerical values were coherent. The relationships resulted in the set of curves shown in Figure 5(a) below. The resulting guide curves are then used by Intellihull to generate a hullform, as shown in Figure 5(c) below. Using Paramarine's analysis capabilities this hullform, consistent with a ship that is balanced in terms of length, weight, and volume, can then be assessed to explore performance characteristics not normally examined during the initial stages of the design process.



(a)

(b)

(c)

Figure 5: Guide Curves (a), Section Curves (b), and Final Hullform (c)

This section has demonstrated the overall process of parametric generation of a hullform using Paramarine Intellihull. The process described is well suited to the studies currently being performed by the MoD, exploring the feasibility of many different tanker design concepts.

There are still some potential areas for improvement with the parametric hullform generation method. The MoD is exploring a number of options including single and twin machinery spaces. Intellihull is currently limited in its ability to represent some types of aft body shapes. Paramarine's developers, GRC Ltd, are currently developing a new hullform generation tool, X-Topology, which has the potential to allow the generation of hullforms from a set of curves with arbitrary complexity. Although potentially increasing the level of hullform definition required, the new functionality will enable the representation of a variety of body shapes while still working within this framework.

3.3 WEIGHT AND VOLUME ESTIMATION

Weight and volume estimation is a key part of concept design. A commonly used and simple method of estimating weight and volume is to scale existing data from previously built, similar ships, by using main particulars such as length, number of crew, or installed power to develop scaling ratios. Estimates of ship cost during early stage design are primarily derived from the weight data generated for a new concept; therefore, the selection of appropriate ratios is an important step in developing realistic costs and a system that can reflect design changes correctly. The selection of scaling ratios for individual weight and volume groups requires an understanding of the variables influencing the weight or size of the group. Hull structural weight for example, can be assumed to be influenced by overall ship dimensions, whereas the size of an accommodation area is likely to be governed by the number of personnel it must accommodate.

The selection of suitable scaling methods to ratio group weight and volume data from similar previously built ships is a critical step in the design process. The data produced is fed back into the other calculations within the iterative process; for instance, total ship weight provides an overall displacement, which is then used in re-calculating the weight of the hull structure, updating the overall displacement, and so forth, thus allowing weight and volume estimates to be updated until convergence is achieved

3.4 FUTURE WORK

The next generation of the model described in this paper is already in development for use in the concept design of more complex future naval auxiliaries such as solid support and seabasing ships. The data flow depicted in Figure 3 becomes much more complex as more variables are needed to define requirements and ship layout. Another important addition is an optimisation loop (shown in Figure 6 below), where system inputs can be updated using genetic algorithms to optimise the design around specified criteria such as cost or cargo transport efficiency. While, it is acknowledged that not all ship characteristics are suited to assessment in this numerical manner it is felt that significant aspects of the design can be explored by adopting this approach.. This subject will, however, form the basis of a future paper.

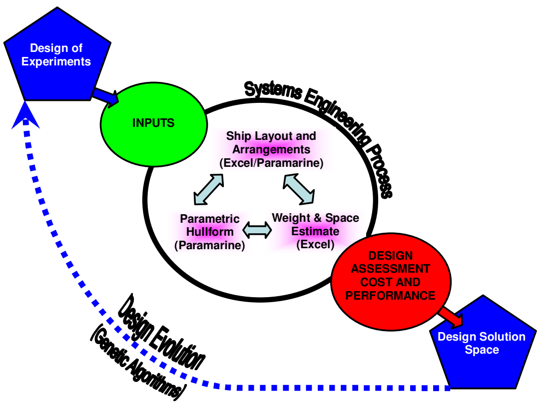


Figure 6: Optimisation Loop Applied to Systems Engineering Process

3.5 COST PREDICTION

Predicting ship costs during early stage design stage is a delicate art, and accordingly the cost estimates described in this study are considered a rough order of magnitude. The cost estimates were performed internally by the MoD (from the point of view of an intelligent customer) and not by shipyards themselves. A common method of cost estimating is to scale costs from ship weights using cost estimating ratios (*CER*). These ratios are based on data gathered from ships that have already been built and procured, and for this study were broken down by weight group. Separate sets of CER's were used to determine material cost (*CM*) and labour cost (*CL*), and the method by which they were summed can be seen in Equation 3 below.

$$CM = \sum_i CER_{M,i} WT_i$$

$$CL = HR \sum_i CER_{L,i} WT_i$$

Equation 3

In order to then derive ship price from the estimated costs, one needs to consider the shipbuilder's profit margin (p):

$$P_{ship} = (1+p)(CL+CM)$$

Equation 4

3.5 (a) Fleet Tanker Costs

Each variation of the Fleet Tanker in this study used the same *CER* values, so costs change only as weights change.

Figure 7 below shows how the baseline Fleet Tanker in this study breaks down both in terms of weight and total cost for the six main categories of systems. Although hull structure makes up the majority of the lightship weight, it accounts for less than one quarter of the total cost of this ship type.

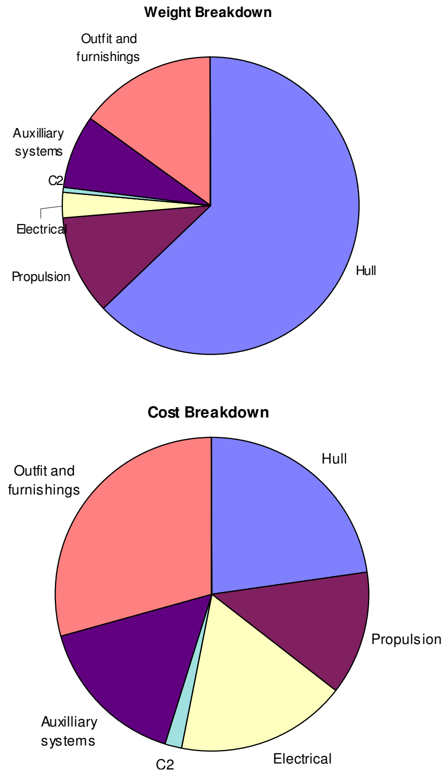


Figure 7: Cost and weight breakdown (lightship) of Fleet Tanker by system

3.5 (b)   Learning Curve

The decrease in build cost exhibited by subsequent ships during batch construction is well known. This benefit is due to the yard gaining expertise and efficiency as it gains experience. In manufacturing this is known as a "learning curve." In accordance with Equation 4 above, the learning curve will affect the labour cost (*CL*) portion of the total price, and will decrease as ship production increases. Learning curve is usually expressed as a percentage that costs will reduce to as production doubles, so if a shipyard suggests an 85% learning curve this means that their second ship has 85% of the labour costs of their first ship and their fourth ship has 85% of the labour costs again of the second ship. The labour costs, thus, will decrease exponentially in the form of Equation 5 below, where *i* denotes the ship number in the series and *LC* is the learning curve expressed as a percent. Equation 5(b) shows the average labour cost of *n* ships.

$$CL_i = CL_1 i^{\log_2 LC} \quad \text{(a)}$$

$$\overline{CL}_n = \frac{CL_1}{n}\sum_{i=1}^{n} i^{\log_2 LC} \quad \text{(b)}$$

Equation 5

It is clear then that the average cost of labour per ship will decrease as the number of ships in a series increases. If one assumes that 85% of the costs of the lead Fleet Tanker are attributed to shipyard labour, and the shipyard has an 85% learning curve, then the average price of six ships should be 81% of the price for a single ship of a unique design. This theory can also be applied to demonstrate the cost advantages a shipyard will have if the Fleet Tankers are based on an existing design currently in production; for instance, if the ships are built as the tenth, eleventh, and subsequent ships produced in an existing series, they would cost ¾ of what they would cost as the lead ships in a series. Even a design that exceeds the minimum MoD requirements can be cost effective if based on an existing production line. Conversely, the Fleet Tanker production line has potential to carry on, at a reduced cost, after the UK ships are completed. The designs may have export potential to other Navies, and the UK MoD contract will add marketing value.

3.6   RESULTS

Figure 8 depicts the relative costs of 48 different configurations of the Fleet Tanker. Costs are presented as a percentage of the highest priced ship depicted. Features considered were speed, type of propulsion system (electric or mechanical), number of propulsors, number of RAS(L) rigs, and the existence of a flight deck and/or hangar for helicopter operations. Although it is an aspiration for the Fleet Tanker to incorporate all such features, budgetary reasons may limit capability. The information developed through the systems engineering approach described in this paper can assist the MoD in understanding important cost tradeoff decisions as final requirements for the Fleet Tankers are incorporated in the ship specification.

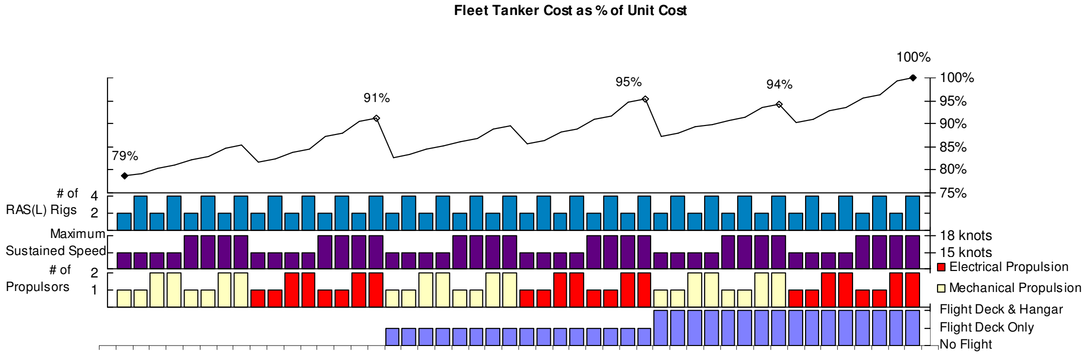


Figure 8: Fleet Tanker relative costs of options

4 CONCLUSIONS

The MoD is developing a new approach to rapid concept design generation and costing. The approach is that of systems engineering, and requires the designer to understand the key principles of ship design in order to manage the design process, and then robustly explore the entire design space for optimum designs. Understanding the full range of possible designs isn't only important for ship performance: the implications of requirements on ship cost are critical for decision makers to understand as they plan the structure of the future Royal Navy in a limited budget environment.

5 REFERENCES

1. Oil Companies International Marine Forum, "Recommendations for Oil Tanker Monifolds and Associated Equipment", Fourth Edition, 1991

2. Lloyd's Register, "Rules and Regulations for the Classification of Naval Ships", Volume 3, Part 1, Chapter 5, 2007

3. "Beyond V5—Paramarine future developments", Forrest, C, Paramarine V5 User Group Day Presentations, 2007

6 AUTHORS' BIOGRAPHIES

Seth Cooper is an employee of Naval Sea Systems Command (NAVSEA) in the United States, and is part of the Surface Ship Design and Force Architecture Department. He brings his concept design expertise to the MoD as part of an engineering exchange program between the US and UK. Prior to working at NAVSEA, he worked at the Naval Surface Warfare Center Carderock Division. He holds a BEng in Mechanical Engineering from the University of Pennsylvania and a Masters in Ocean Engineering from Virginia Tech.

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Appendix C

Complexity Analysis of Different Design Approaches

This section provides a summary of the comparison of the following design approaches:

- Case A: Brute Force
- Case B: Deterministic Optimisation
- Case C: Stochastic Optimisation
- Case D: Simple Library
- Case E: Library with Separation and Combination
- Case F: Library with Separation, Combination and Delayed Calculations
- Case G: Library with Separation, Staged Combination and Delayed Calculations

These seven approaches are modelled via simple relationship that are intended to explore the behaviour of the different methods as the problems they addresses change. Solutions produced my the library methods may not be comparable to those developed by optimisation methods, as optimisation methods are far more efficient at closing in on a single point.

C.1 Definitions

C.1.1 Number of Operations, Styles and Variables

This section defines the values of a number of key inputs required for the equations modelling the seven different cases. These variables are shown in Table C.1.

Table C.1: Basic Variables

Variable	Description	Definition
S	Styles per Group	$S = 10$
G	Groups	$G = 3$
R	Requirements	$R = 30$
V_{In}	Input variables per group option	$V_{\text{In}} = 5$
V_{GrpCalc}	Calculated variables per group option	$V_{\text{GrpCalc}} = 5$
V_{GrpTotal}	Total variables per group option	$V_{\text{GrpTotal}} = V_{\text{In}} + V_{\text{GrpCalc}}$
V_{CalcComb}	Calculated variables per combined option	$V_{\text{CalcComb}} = 5G$
V_{TotalVar}	Total variables per combined option	$V_{\text{TotalVar}} = V_{\text{GrpTotal}}G + V_{\text{CalcComb}}$
X	Number of values for each variable	$X = n$
O_{Grp}	Number of options per group	$O_{\text{Grp}} = SX^{V_{\text{In}}}$
O_{Total}	Total number of combined options	$O_{\text{Total}} = O_{\text{Grp}}^{G}$

A number of specific assumption are required for the optimisation methods. These values are shown in Table C.2.

Table C.2: Variables for Optimisation Methods

Variable	Description	Definition
O_{Step}	Objects considered in each optimisation step	$O_{\text{Step}} = 100$
Itt_{detr}	Iterations required by deterministic optimisation methods	$\text{Itt}_{\text{detr}} = 10$
$\text{Itt}_{\text{stock}}$	Iterations required by stochastic optimisation methods	$\text{Itt}_{\text{stoch}} = 10$

C.1.2 Durations for Different Type of Operations

This section defines the relative duration take for different operations that existing in the different cases. The durations of six key operations are shown in Table C.3 and refer to the time take to act upon one variable or option as descried in the table. Due to the large number of variables in the calculation process these times should be regarded as indicative of the likely duration. Actual durations will depend upon the performance of the computer executing the code and the calculation methods employed.

Table C.3: Time Required per Operation

Variable	Description	Duration
T_{rand}	Time to obtain a random input	$T_{\text{rand}} = 1$
T_{calc}	Time to calculate one performance characteristic	$T_{\text{calc}} = 100000$
$T_{\text{calcQuick}}$	Time to performance a simple calculation (i.e. interpolation)	$T_{\text{calcQuick}} = 1000$
$T_{\text{downselect}}$	Time required to down select a single option	$T_{\text{downselect}} = 1000$
T_{comb}	Time required to produce new combined option	$T_{\text{comb}} = 1000$
T_{nextSoln}	Time to develop a further option (for optimisation methods)	$T_{\text{nextSoln}} = 1000$

C.1.3 Down Select Step Controls

Simple controls for the down select steps. F_{removed} sets the fraction of the options that will remain after a single requirement is applied to down select a set of options.

$$F_{\text{remaining}} = 0.5$$

The time take to perform a down select operation is found by product of time for each individual down select step ($T_{\text{downselect}}$) and the number of operation in each step. Clearly as each requirement is applied options are removed. This reduces the options that must be considered at each step. This is modelled via the following relationship

C.2 Existing Approaches

C.2.1 Case A: Brute Force

This section determines the time needed to find the solutions meeting a set of requirements via a brute force approach.

No pre-calculation is performed, therefore the time required for pre-calculation in this case ($\mathrm{T1}_{\text{pre}}$) is:

$$\mathrm{T1}_{\text{pre}} = 0$$

The run time is found from the summation of the following three elements:

- the time to generate the input data for the input variables;
- the calculation time for the other variables;

- the time required to down select the acceptable solutions.

The time to generate the input data for the input variables is the product of the number of options being considered (O_{Total}), the time required to construct a random input (T_{rand}), the number of input variables per group (V_{In}) and the number of groups (G). The calculation time for the remaining variables can be determined from the number of items requiring calculation, given by the sum of the values that must be found (i.e. $V_{\text{GrpCalc}}G+V_{\text{CalcComb}}$), multiplied by the calculation time (T_{calc}) and number of options (O_{Total}). Finally, the time required to down select the acceptable solutions can be found by multiplying the time required to down select a single options ($T_{\text{downselect}}$) by the number of options remaining. The number of options remaining after a given number of requirements (r) have applied can be found by multiplying the total number of options (O_{Total}) by the fraction of options remaining after a single option is applied ($F_{\text{remaining}}$) raised to the power r. The total time required for a number of requirements (R) to be applied is sum of options removed between $r = 0$ and $r = R - 1$.

$$\begin{aligned}
\mathrm{T1}_{\text{run}} &= T_{\text{rand}}O_{\text{Total}}V_{\text{In}}G + \ T_{\text{calc}}O_{\text{Total}}\left(V_{\text{GrpCalc}}G + V_{\text{CalcComb}}\right) \\
&+ \ \sum_{r=0}^{R-1}\left(T_{\text{downselect}}O_{\text{Total}}{F_{\text{remaining}}}^{r}\right) \\
&= 3.00201\times10^{9}n^{15}
\end{aligned}$$

C.2.2 Case B: Deterministic Optimisation

This section determines the time a deterministic optimisation method would require to find a solution. It should be remembered that this method can only be successfully applied solution space is continuous. Also, deterministic optimisation methods may become 'stuck' in local optima and, hence, may not find a global optimum.

Once again no pre-calculation is performed, therefore:

$$\mathrm{T2}_{\text{pre}} = 0$$

The run time is found using the following elements:

- the time to generate the input data for the input variables;
- the calculation time for the remaining variables;
- and the time required to down select the acceptable solutions.

The assumption has been made that the deterministic optimisation method must be run once for each combination of sub-group styles.

$$\begin{aligned} \mathrm{T2}_{\mathrm{run}} &= \left(T_{\mathrm{rand}} V_{\mathrm{In}} G + \left(T_{\mathrm{calc}} \left(V_{\mathrm{GrpCalc}} G + V_{\mathrm{CalcComb}}\right) + T_{\mathrm{nextSoln}} V_{\mathrm{In}}\right) \mathrm{Itt}_{\mathrm{detr}}\right) S^G \\ &= 3.00500{\times}10^{10} \end{aligned}$$

C.2.3 Case C: Stochastic Optimisation

This section estimates the time needed to find a solution via a systematic optimisation method, such as a genetic algorithm. Compared to the deterministic optimisation method presented in Case B a stochastic optimisation method is able to avoid becoming stuck in local optima.

No pre-calculation is performed when applying a stochastic optimisation method, therefore:

$$\mathrm{T3}_{\mathrm{pre}} = 0$$

The run time is found using the following elements:

- the time to generate the initial population for the input variables;
- the calculation time for the variables for each option in the current population;
- and the time needed to generate a solution from the next iteration.

As with the deterministic optimisation method, the assumption has been made that the stochastic optimisation method must be run once for each combination of sub-group styles.

$$\begin{aligned} \mathrm{T3}_{\mathrm{run}} = S^G \big(&T_{\mathrm{rand}}\ V_{\mathrm{In}} G O_{\mathrm{Step}} \\ &+ \left[\ T_{\mathrm{calc}} \left(V_{\mathrm{GrpCalc}} G + V_{\mathrm{CalcComb}}\right) + \ T_{\mathrm{nextSoln}} V_{\mathrm{In}}\right] O_{\mathrm{Step}} \mathrm{Itt}_{\mathrm{stoch}}\big) \\ &= 3.00500{\times}10^{12} \end{aligned}$$

C.3 Library Base Approach

C.3.1 Setup Definitions

Three functions are defined here, the first returns the number of options remaining after a number of down select steps while the second calculates the duration of the down select process and the final function finds the down select duration when fetching items from a library. Both use the initial number of options and the number of down select steps that have occurred as inputs. These functions are used within Cases D to G.

$$\mathrm{OptionsPostDownselect}[\mathrm{OptionInput}, \mathrm{NumberOfDownselects}] := \mathrm{OptionInput} \left(F_{\mathrm{remaining}}^{\mathrm{NumberOfDownselects}}\right)$$

$$\text{DownselectDuration}[\text{OptionInput}, \text{NumberOfDownselects}] := \sum_{x=0}^{\text{NumberOfDownselects}-1} \left(T_{\text{downselect}} \text{OptionInput} F_{\text{remaining}}^{x}\right)$$

$$\text{DownselectDurationFromLibrary}[\text{OptionInput}, \text{NumberOfDownselects}] := \text{Log}\left[2, \sum_{x=0}^{\text{NumberOfDownselects}-1} \left(T_{\text{downselect}} \text{OptionInput} F_{\text{remaining}}^{x}\right)\right]$$

It is also necessary to divide the initial set of requirements (R) into two sets, the group requirements (R_{grp}) and combined requirements (R_{comb}) which can then be used to down select group and combined options.

$$R_{\text{grp}} = \text{Round}[R/(G+1), 1] = 8$$

$$R_{\text{comb}} = \text{Round}\left[R - GR_{\text{grp}}, 1\right] = 6$$

C.3.2 Case D: Simple Library Based

This section determines the time required to find acceptable options via using a simple library based approach adapted from the brute force approach described in Case A. However, as opposed to Case A the values for the options have been pre-calculated and stored in a library. The part of Case A which can be recalculated were:

- the time to generate the input data for the input variables;
- the calculation time for the other variables;

Consequently, the time required for these two part of the calculation form the pre-calculation time for this case.

$$\begin{aligned} \text{T4}_{\text{pre}} &= T_{\text{rand}} O_{\text{Total}} V_{\text{In}} G + \ T_{\text{calc}} O_{\text{Total}} \left(V_{\text{GrpCalc}} G + V_{\text{CalcComb}}\right) \\ &= 3.00002{\times}10^{9} n^{15} \end{aligned}$$

The run time is now simply the time required to down select the options from the library to find those that are acceptable. This can be found using the function for determining the down select duration described above .

$$\begin{aligned} \text{T4}_{\text{run}} &= \text{DownselectDurationFromLibrary}\left[O_{\text{Total}}, R\right] \\ &= \frac{\text{Log}\left[2. \times 10^{6} n^{15}\right]}{\text{Log}[2]} \end{aligned}$$

C.3.3 Case E: Library with Separation and Combination

This section determines the time needed to find acceptable options using a library comprising of sub-group options, that are pre-calculated before the designer begins using the tool to examine a set of requirements.

Values for each sub-group option must be pre-calculated and stored, therefore:

$$\begin{aligned} \mathrm{T5}_{\mathrm{pre}} &= T_{\mathrm{rand}} O_{\mathrm{Grp}} V_{\mathrm{In}} G + \; T_{\mathrm{calc}} O_{\mathrm{Grp}} V_{\mathrm{GrpCalc}} G \\ &= 1.50002{\times}10^{7} n^{5} \end{aligned}$$

The run time is found using the following elements:

- the time required to down select the options from the library to find those that are acceptable;
- the time needed to combine these sub-options into new combined options;
- the calculation time for the unknown characteristics of the combined options;
- and the time needed to down select the combined options.

It is convenient to determine the options remaining in each sub-group following the initial down select (O_1) and the number of combined options when these remaining sub-group options are combined (O_{Combined}).

$$O_1 = \mathrm{OptionsPostDownselect}\left[O_{\mathrm{Grp}}, R_{\mathrm{grp}}\right]$$

$$O_{\mathrm{Combined}} = O_1^G$$

Using these values it is possible to find the four components of the run time duration for this case, as shown below. The assumption has been made that each characteristics can be calculated using a quick calculation method.

$$\begin{aligned} \mathrm{T5}_{\mathrm{run}} = \; & G\,\mathrm{DownselectDurationFromLibrary}\left[O_{\mathrm{Grp}}, R_{\mathrm{grp}}\right] + T_{\mathrm{comb}} O_{\mathrm{Combined}} \\ & + T_{\mathrm{calcQuick}} V_{\mathrm{CalcComb}} O_{\mathrm{Combined}} + \mathrm{DownselectDuration}\left[O_{\mathrm{Combined}}, R_{\mathrm{comb}}\right] \\ & = 1.07102 n^{15} + \frac{3\mathrm{Log}\left[19921.9 n^{5}\right]}{\mathrm{Log}[2]} \end{aligned}$$

C.3.4 Case F: Library with Separation, Combination and Delayed Calculations

As with case E, in this case values for each sub-group option must be pre-calculated and stored, therefore:

$$\begin{aligned}\mathrm{T6}_{\mathrm{pre}} &= T_{\mathrm{rand}} O_{\mathrm{Grp}} V_{\mathrm{In}} G + \; T_{\mathrm{calc}} O_{\mathrm{Grp}} V_{\mathrm{GrpCalc}} G \\ &= 1.50002{\times}10^{7} n^{5}\end{aligned}$$

The run time is found using the following elements:

- the time required to down select the options from the library to find those that are acceptable;
- the time needed to combine these sub-options into new combined options;
- the calculation time for the unknown characteristics of the combined options;
- and the time needed to down select the combined options.

As with Case E the options remaining after down selecting the sub-options from the library, therefore:

$$O_1 = \mathrm{OptionsPostDownselect}\left[O_{\mathrm{Grp}}, R_{\mathrm{grp}}\right]$$

$$O_{\mathrm{Combined}} = O_1^G$$

However, in this case the calculations for each of the characteristics is delayed until it is requires by a given requirement.

$$\begin{aligned}&\mathrm{DownselectedOptions[DownselectStep]}{:=} \\ &\qquad\qquad \mathrm{OptionsPostDownselect[DownselectedOptions[DownselectStep} - 1], 1]\end{aligned}$$

$$\mathrm{DownselectedOptions[0]} = O_{\mathrm{Combined}}$$

Therefore, the run time can be described by the following equation where the final term gives the sum of the calculation time and down select time for each of the group level requirements (the assumptions has been made that one calculation must be performed for each requirement that is assessed):

$$
\begin{aligned}
\mathrm{T6}_{\mathrm{run}} = & \; G\mathrm{DownselectDurationFromLibrary}\left[O_{\mathrm{Grp}}, R_{\mathrm{grp}}\right] + T_{\mathrm{comb}} O_{\mathrm{Combined}} \\
& + \sum_{r=1}^{R_{\mathrm{grp}}} \left(T_{\mathrm{calcQuick}} \mathrm{OptionsPostDownselect}\left[O_{\mathrm{Combined}}, r\right]\right. \\
& \left. + T_{\mathrm{downselect}} \mathrm{OptionsPostDownselect}\left[O_{\mathrm{Combined}}, r\right]\right) \\
& = 0.17835 n^{15} + \frac{3\mathrm{Log}\left[19921.9 n^{5}\right]}{\mathrm{Log}[2]}
\end{aligned}
$$

C.3.5 Case G: Library with Separation, Staged Combination and Delayed Calculations

This section determines the time required to find a solution using a Library Based method that utilises separation, stage combination and delayed calculations.

As with Case E and F values are pre-calculated and stored, therefore:

$$
\begin{aligned}
\mathrm{T7}_{\mathrm{pre}} &= T_{\mathrm{rand}} O_{\mathrm{Grp}} V_{\mathrm{In}} G + \; T_{\mathrm{calc}} O_{\mathrm{Grp}} V_{\mathrm{GrpCalc}} G \\
&= 1.5000150 \times 10^{7} n^{5}
\end{aligned}
$$

The run time is found using the following elements:

- the time required to down select the options from the library to find those that are acceptable;
- the time needed to combine these sub-options into new combined options;
- the calculation time for the unknown characteristics of the combined options;
- and the time needed to down select the combined options.

As with Case F the options remaining after down selecting the sub-options from the library. However, in this case the combination operation will be undertaken in stages. Additionally the calculation of characteristics can be delayed until the characteristic is required to find a requirement. It is useful to define a number of functions that describe the objects remaining after a number of combination and down select operations have been performed.

First the number of requirements used to down select the combined options (R_{comb}) must be split into requirements that will be applied at the different stages (R_{staged}). The following equation finds this value, rounded to the closest whole number.

$$
R_{\mathrm{staged}} = \mathrm{Round}\left[R_{\mathrm{comb}} / \left(G - 1\right), 1\right] = 3
$$

It is helpful to define three functions, these calculate the following values:

- The number of options produced after the Mth group of options has been combined is given by the function OptCombinedInitial[M];
- The number of options that remain after the Mth group of options have been combined and the requirements (R_{staged}) used to down select the acceptable solutions is given be the function OptCombinedFinal[M];
- Finally, the options remaining after Mth group of options have been added and the Nth set of requirements have been used to remove unacceptable option.

The three functions are shown below:

$$\begin{aligned}&\text{OptCombinedInitial[GroupNumber]:=}\\&\qquad\qquad\text{OptCombinedFinal[1]OptCombinedFinal[GroupNumber} - 1]\end{aligned}$$

$$\text{OptCombinedFinal[GroupNumber]:=OptDownselected}\left[\text{GroupNumber}, R_{\text{staged}}\right]$$

$$\begin{aligned}&\text{OptDownselected[GroupNumber, RequirementNumber]:=}\\&\quad\text{OptionsPostDownselect}[\text{OptCombinedInitial[GroupNumber]}, \text{RequirementNumber}]\end{aligned}$$

Next we can define the value of the function for OptCombinedFinal[1] using the number of sub-options remaining after the group requirements are used to down select the group options from the library.

$$\text{OptCombinedFinal}[1] = \text{OptionsPostDownselect}\left[O_{\text{Grp}}, R_{\text{grp}}\right]$$

$$\begin{aligned}\text{T7}_{\text{run}} = \;& G\text{DownselectDurationFromLibrary}\left[O_{\text{Grp}}, R_{\text{grp}}\right]\\&+\sum_{g=2}^{G}\left(\sum_{r=1}^{R_{\text{staged}}}(T_{\text{comb}}\text{OptDownselected}[g,r]\right.\\&+T_{\text{calcQuick}}\text{OptDownselected}[g,r]\\&\left.+T_{\text{downselect}}\text{OptDownselected}[g,r])\right)\\&= 4.00543n^{10} + 0.0195578n^{15} + \frac{3\text{Log}\left[19921.9n^5\right]}{\text{Log}[2]}\end{aligned}$$

C.4 Comparison

C.4.1 Run Times

Using these seven different cases the effect of exploring different numbers of options can be explored. By varying the number of possible values each sub-group variable (X) can take the number of options in the sub groups can be altered allowing the pre-calculation and run times for the different cases to be explored.

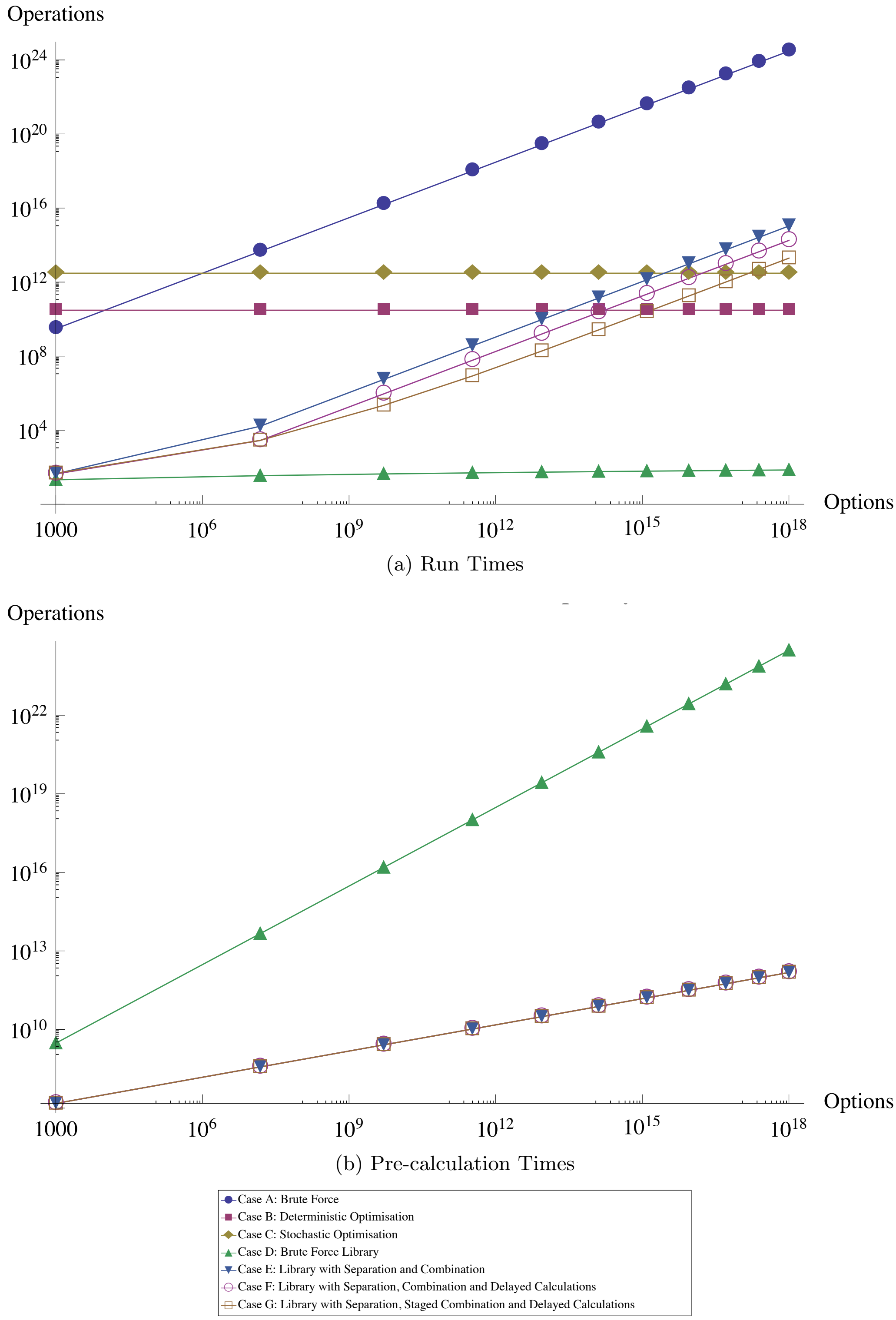


Figure C.1: Pre-calculation and Run Times for Cases A–G

Appendix D

Exploratory Implementation Example

This appendix provides detailed example of options are generated, down selected in the exploratory implementation. Section D.1 details an example of generation method for the sub-options. Section D.2 provides an example of how a set of requirements are assessed.

D.1 Example of Library Generation

This section provides an example of the steps taken in generating the library of sub-options.

D.1.1 Creation of Float Sub-Options

The Float functional group sub-options were generated from a number of input design variables as shown in Table D.1. The first column simply provides a unique identifier to enable designs to be tracked through the spread-sheet's numerous sheet.

Table D.1: Input Float Functional Group Design Variables

Solution Identifier	Input Variables					
	Δ [te]	ρ [n/a]	D [m]	C_b [n/a]	KG [m]	vs [%]
float_id_1	5438	0.42	10.52	0.55	6.84	0.26
float_id_2	5975	0.39	10.44	0.45	6.82	0.12
float_id_3	4675	0.37	12.42	0.47	6.73	0.25
float_id_4	5132	0.28	10.48	0.45	6.79	0.15
float_id_5	4191	0.31	12.12	0.49	8.36	0.27
float_id_6	4181	0.28	11.87	0.46	6.41	0.26
float_id_7	4031	0.45	9.90	0.58	6.87	0.20
float_id_8	4155	0.25	11.83	0.57	6.90	0.20
⋮	⋮	⋮	⋮	⋮	⋮	⋮

From these six variables the values of the remaining significant hullform characteristics could be determined by applying hydrostatic and stability considerations as shown in Table D.2.

Table D.2: Determining Characteristics from Hydrostatic and Stability

Solution Identifier	Input Variables Δ $[te]$	$\cdots$	vs $[\%]$	From Geometry Vm $[m^3]$	L $[m]$	B $[m]$	T $[m]$	$\cdots$	Cost $[£k]$
float_id_1	5438	$\cdots$	0.32	9638	77.6	19.26	6.65	$\cdots$	24503
float_id_2	5975	$\cdots$	0.31	13376	134.3	16.78	5.85	$\cdots$	38222
float_id_3	4675	$\cdots$	0.28	9405	77.2	17.22	7.48	$\cdots$	25184
float_id_4	5132	$\cdots$	0.24	15372	154.9	15.90	4.63	$\cdots$	43420
float_id_5	4191	$\cdots$	0.27	10007	67.5	20.36	6.20	$\cdots$	24754
float_id_6	4181	$\cdots$	0.36	10924	96.1	16.25	5.81	$\cdots$	29282
float_id_7	4031	$\cdots$	0.34	7281	58.2	19.81	6.01	$\cdots$	18120
float_id_8	4155	$\cdots$	0.35	13263	94.4	18.03	4.29	$\cdots$	31275
$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$

Once the hullform's characteristics were fixed two performance analysis methods were applied to give a measure of the ship resistance, in the form of a power-speed curve, and an assessment of seakeeping performance, via a comparative seakeeping rank. Example results are as shown in Table D.3.

Table D.3: Determining Performance

Solution Identifier	Input Variables Δ $[te]$	$\cdots$	vs $[\%]$	From Geometry Vm $[m^3]$	$\cdots$	Cost $[£k]$	From Powering 10 $[kts]$	$\cdots$	40 $[kts]$	Seakeeping Bales rank $[n/a]$
float_id_1	5438	$\cdots$	0.26	9638	$\cdots$	24503	0.6	$\cdots$	205.8	-20
float_id_2	5975	$\cdots$	0.12	13376	$\cdots$	38222	0.7	$\cdots$	83.9	-6
float_id_3	4675	$\cdots$	0.25	9405	$\cdots$	25184	0.6	$\cdots$	154.0	-29
float_id_4	5132	$\cdots$	0.15	15372	$\cdots$	43420	0.7	$\cdots$	64.5	-3
float_id_5	4191	$\cdots$	0.27	10007	$\cdots$	24754	0.5	$\cdots$	178.9	-28
float_id_6	4181	$\cdots$	0.26	10924	$\cdots$	29282	0.6	$\cdots$	111.8	-17
float_id_7	4031	$\cdots$	0.20	7281	$\cdots$	18120	0.5	$\cdots$	235.5	-30
float_id_8	4155	$\cdots$	0.20	13263	$\cdots$	31275	0.6	$\cdots$	156.6	-8
$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$

This step resulted in the creation of 1944 Float functional group sub-options.

D.1.2 Creation of Move and Infrastructure Sub-Options

Similarly, sub-options were generated for the Move and Infrastructure functional groups. Initially 616 Move and 36 Infrastructure functional group sub-options where generated.

D.2 Example of Applying Requirements in the Exploratory Implementation

This section presents the detailed steps that are undertaken when using the exploratory implementation and the library of sub-options (as described in Section D.1) to explore a set of design requirements. It is important to note that this set of requirements are only representative and are defined by the designer as they use the tool. Other requirements or sets of requirements can be specified within the tool and it is possible to impose an arbitrary number of requirements upon any of the down select steps.

D.2.1 Float Sub-Options Down Select

The next step in the solution process was the down select of the Float functional group sub-options in response to a number of input requirements. The four requirements used for this down select were:

- Draught $< 6m$;
- Length $< 160m$;
- Beam $< 20m$;
- Power at a Speed of $30kts < 55MW$.

Three of these—draught, length and beam constrains—corresponded to requirements on ship size originating from a docking constrain defined by a customer. The powering requirement is representative of a potential requirement intended to limit installed powers of the Move sub-options to a lower cost range. Table D.4 shows the impact each constraint has upon the number of Float functional sub-options remaining during the down select process. The step reduced the initial 1944 Float functional group sub-options to 368 sub-options able to satisfy the requirements.

Table D.4: Remaining Float Functional Group Sub-Options

Step	Additional Requirement Applied	Number of Remaining Sub-Options
1	None	1944
2	Draught $< 6m$	768
3	Length $< 160m$	727
4	Beam $< 20m$	663
5	Power at a Speed of $30kts < 55MW$	368

D.2.2 Move Sub-Options Down Select

From the initial 616 Move functional group sub-options that where generated 224 remained after the down select process. The requirements used for the down select where:

- Cost < £150,000k;
- Power < 55MW.

The cost requirement was representative of the maximum total ship cost. The power constraint matched the limitation on the installed powers of the Float sub-options to a lower cost range. Details of the requirements used are shown in Table D.5.

Table D.5: Remaining Move Functional Group Sub-Options

Step	Additional Requirement Applied	Number of Remaining Sub-Options
1	None	616
2	Cost < £150,000k	616
3	Power < 55MW	276

D.2.3 Infrastructure Sub-Options Down Select

Similarly, 36 Infrastructure functional group sub-options were initially generated. These were down selected using two requirements :

- Endurance > 26 days;
- Officers > 14.

The endurance requirement originated directly from the required mission duration. The officers requirement originating from the demands of the payload. The impact of the requirements upon the options available are shown in Table D.6.

Table D.6: Remaining Infrastructure Functional Group Sub-Options

Step	Additional Requirement Applied	Number of Remaining Sub-Options
1	None	36
2	Endurance > 26 days	35
3	Officers > 14	14

D.2.4 Combination of Float and Move Sub-Options

At this stage we have sufficient information to proceed with combining the Float and Move functional group sub-options. All possible permutations of the remaining Float and Move sub-options are generated and then simple additional calculations are used to assess the maximum speed and a speed-range profile. This combination of 368 Float group sub-options and 276 Move group sub-options created over 70,000 combined Float–Move options. A selection of the results are summarised in Table D.7 (see page 281) which shows the combined Float–Move options together with the combined option characteristics. The two columns labelled 'PM 1' and 'PM 2' indicate the prime movers which form part of the move functional group. The prime movers names have been abbreviated; '12PA6B' and '16PA6B' are diesel engines produced by Pielstick and the 'LM6000' is a gas turbine produced by General Electric.

D.2.5 Combined Float–Move Options Down Select

Now that the combined Float–Move options are available another set of down selections can be undertaken with a new set of criteria. In this case the requirements used for this down select were:

- Range at $15kts > 9000nm$;
- Top speed $> 28kts$;
- Range at $20kts > 5000nm$;
- Range at $25kts > 2500nm$.

The impact of each of these constraints is shown in Table D.8. It is interesting to note that the final two requirements have no actual impact upon the number of remaining combined options. The fuel carried to satisfy the range requirement of $9000nm$ at $15kts$ is more than sufficient to fulfil either a range of $5000nm$ at $20kts$ or a range of $2500nm$ at $25kts$. This down select process reduced the number of combined Float–Move options from over 70,000 to 3289 options.

Table D.8: Remaining Combined Float and Move Options

Step	Additional Requirement Applied	Number of Remaining Combined Options
1	None	79858
2	Range at $15kts > 9000nm$	8980
3	Top speed $> 28kts$	3289
4	Range at $20kts > 5000nm$	3289
5	Range at $25kts > 2500nm$	3289

D.2.6 Combination of Float–Move and Infrastructure Options

The final combination step combines the down selected Infrastructure options with the remaining combined Float–Move options. As before the different possible permutations

Table D.7: Combined Float and Move Functional Group Options

Float Functional Group Sub-Option					Move Functional Group Sub-Option						Combined Option Characteristics				
Solution	Float Characteristics				Solution	Move Characteristics					Top speed	Range @ Speed [kts]			
Identifier	∇	L	⋯	Bales rank	Identifier	PM 1	PM 2	Fuel	⋯	Power		10	⋯	20	⋯
	[te]	[m]	⋯	[n/a]				[te]	⋯	[MW]	[kts]	[nm]	⋯	[nm]	⋯
float_id_4	5132	154.9	⋯	-3	move_id_1	no engine	LM500	300	⋯	2.9	15.8	3617	⋯	0	⋯
float_id_4	5132	154.9	⋯	-3	move_id_3	no engine	12PA6B	300	⋯	3.1	16.1	9007	⋯	0	⋯
float_id_4	5132	154.9	⋯	-3	move_id_4	LM500	12PA6B	300	⋯	6.0	19.5	9007	⋯	0	⋯
float_id_4	5132	154.9	⋯	-3	move_id_5	12PA6B	12PA6B	300	⋯	6.2	19.7	9007	⋯	0	⋯
float_id_4	5132	154.9	⋯	-3	move_id_6	no engine	16PA6B	300	⋯	4.1	17.5	6563	⋯	0	⋯
float_id_4	5132	154.9	⋯	-3	move_id_7	LM500	16PA6B	300	⋯	7.0	20.4	6563	⋯	3821	⋯
⋮	⋮	⋮	⋱	⋮	⋮	⋮	⋮	⋮	⋱	⋮	⋮	⋮	⋱	⋮	⋱
float_id_4	5132	154.9	⋯	-3	move_id_466	LM500	2×12PA6B	600	⋯	9.1	22.0	8404	⋯	9554	⋯
float_id_17	5696	125.7	⋯	-4	move_id_1	no engine	LM500	300	⋯	2.9	15.7	3617	⋯	0	⋯
float_id_17	5696	125.7	⋯	-4	move_id_3	no engine	12PA6B	300	⋯	3.1	16.0	9007	⋯	0	⋯
⋮	⋮	⋮	⋱	⋮	⋮	⋮	⋮	⋮	⋱	⋮	⋮	⋮	⋱	⋮	⋱
float_id_17	5696	125.7	⋯	-4	move_id_466	LM500	2×12PA6B	600	⋯	9.1	20.8	8404	⋯	9554	⋯
float_id_21	3592	113.7	⋯	-10	move_id_1	no engine	LM500	300	⋯	2.9	16.1	3617	⋯	0	⋯
float_id_21	3592	113.7	⋯	-10	move_id_3	no engine	12PA6B	300	⋯	3.1	16.4	9007	⋯	0	⋯
float_id_21	3592	113.7	⋯	-10	move_id_4	LM500	12PA6B	300	⋯	6.0	19.2	9007	⋯	0	⋯
⋮	⋮	⋮	⋱	⋮	⋮	⋮	⋮	⋮	⋱	⋮	⋮	⋮	⋱	⋮	⋱

are produced and then simple calculations are used to determine the important overall characteristics of each option which is generated. By combining the 3289 Float–Move options with the 8 Infrastructure options over 26,000 combined Float–Move–Infrastructure options are generated. The overall characteristics assessed were the cost of each combined option and values for the combined option's remaining mass and volume. The remaining mass ($M_{remaining}$) in any design can be found by subtracting the combined mass of the three functional groups from the displacement provided by the Float functional group.

$$M_{remaining} = \Delta - (M_{float} + M_{move} + M_{inf})$$

Similarly, the remaining volume ($V_{remaining}$) is given by subtracting the volume utilised by the three functional groups from the total enclosed volume (V) of the Float functional group option.

$$V_{remaining} = V - (V_{float} + V_{move} + V_{inf})$$

D.2.7 Combined Float, Move and Infrastructure Options Down Select

Now that the complete combined options are available a final set of down selections can be undertaken to obtain the final options. In this case the requirements used for this down select were:

- Available Mass > $640te$;
- Available Volume > $7350m^3$;
- Cost < £150,000k.

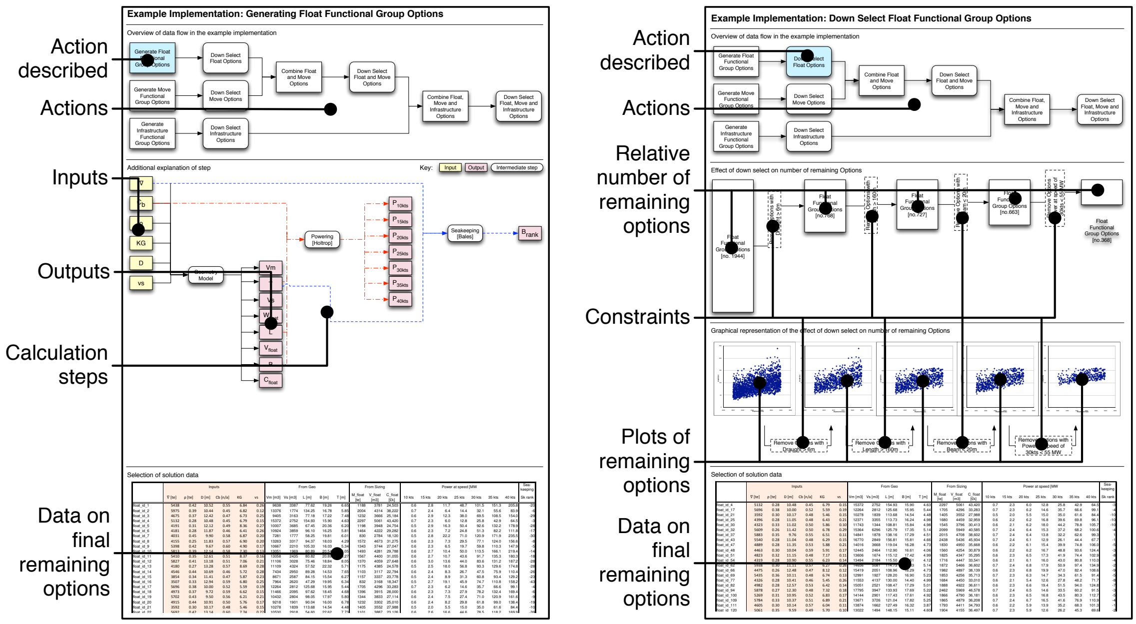
The impact of each constraint is shown in Table D.9. This down select step resulted in the over 26,000 initial combined Float–Move–Infrastructure options being reduced to 822 whole ship options which fulfil the requirements.

Table D.9: Remaining Combined Float, Move and Infrastructure Options

Step	Additional Requirement Applied	Number of Remaining Combined Options
1	None	26312
2	Available Mass > $640te$	5419
3	Available Volume > $7350m^3$	832
4	Cost < £150,000k	822

D.3 Exploratory Study

This section contains example of the output obtained when using the exploratory implementation. Figure D.1 provides an guide of the layout of the results presented in the remainder of this section.

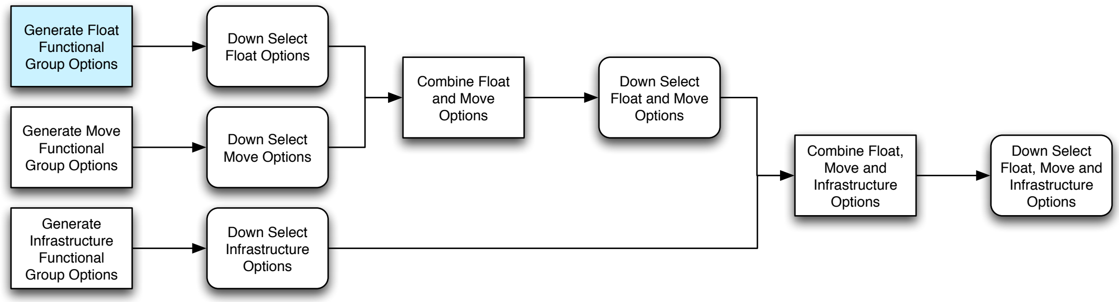


(a) Pages for Generate or Combine Actions (b) Pages for Down Select Actions

Figure D.1: Guide to Exploratory Study Results Presented within this Section

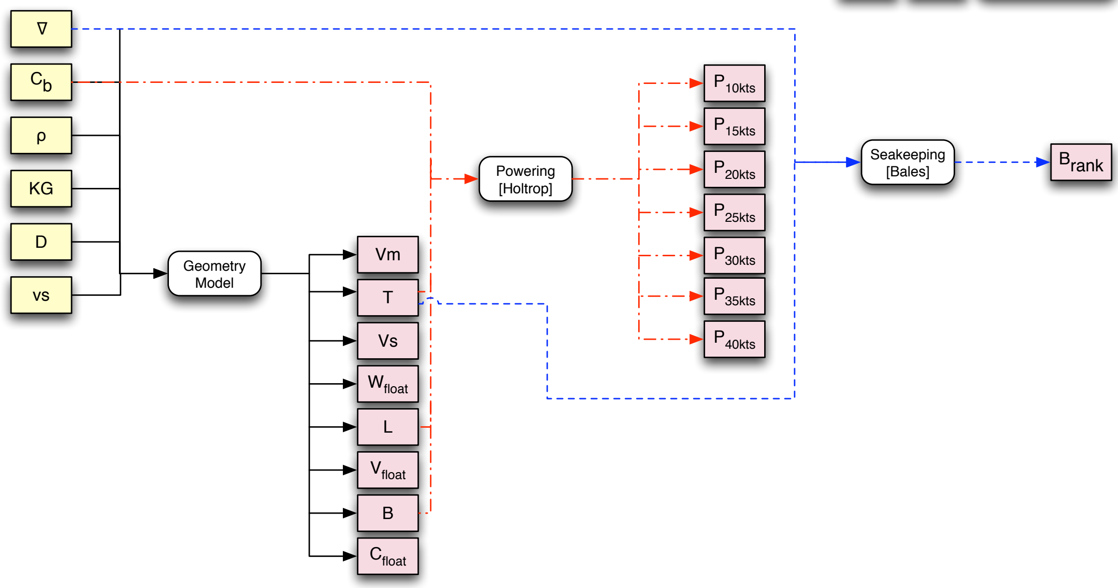
Example Implementation: Generating Float Functional Group Options

Overview of data flow in the example implementation



Additional explanation of step

Key: Input | Output | Intermediate step

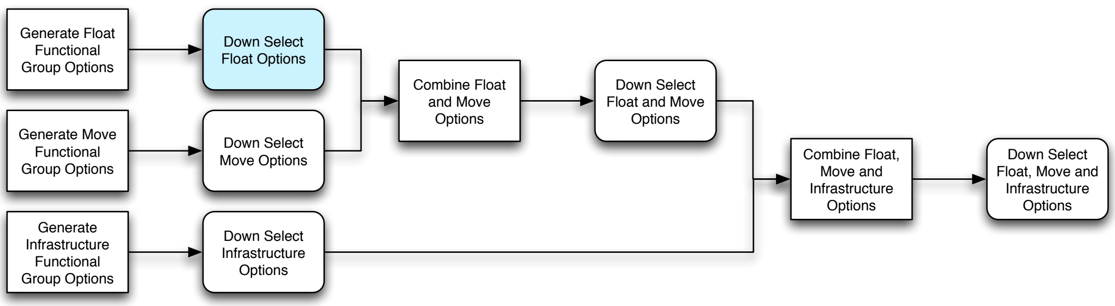


Selection of solution data

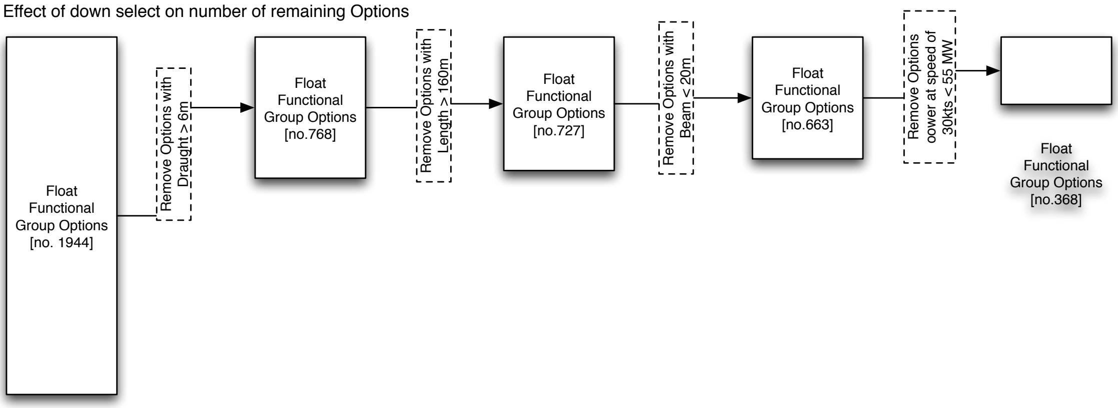
	Inputs						From Geo					From Sizing			Power at speed [MW							Sea-keeping
	∇ [te]	ρ [te]	D [m]	Cb [n/a]	KG	vs	Vm [m3]	Vs [m3]	L [m]	B [m]	T [m]	M_float [te]	V_float [m3]	C_float [£k]	10 kts	15 kts	20 kts	25 kts	30 kts	35 kts	40 kts	Sk rank
float_id_1	5438	0.42	10.52	0.55	6.84	0.26	9638	3387	77.62	19.26	6.65	1188	3781	24,503	0.6	2.8	11.7	48.7	101.5	151.3	205.8	-20
float_id_2	5975	0.39	10.44	0.45	6.82	0.12	13376	1774	134.25	16.78	5.85	2004	4314	38,222	0.7	2.4	6.4	14.4	32.1	55.6	83.9	-6
float_id_3	4675	0.37	12.42	0.47	6.73	0.25	9405	3163	77.18	17.22	7.48	1232	3666	25,184	0.6	2.9	12.3	38.0	69.5	108.5	154.0	-29
float_id_4	5132	0.28	10.48	0.45	6.79	0.15	15372	2752	154.93	15.90	4.63	2297	5061	43,420	0.7	2.3	6.0	12.8	25.8	42.9	64.5	-3
float_id_5	4191	0.31	12.12	0.49	8.36	0.27	10007	3685	67.45	20.36	6.20	1198	3948	24,754	0.5	2.9	16.3	50.4	92.6	132.2	178.9	-28
float_id_6	4181	0.28	11.87	0.46	6.41	0.26	10924	3859	96.10	16.25	5.81	1464	4222	29,282	0.6	2.3	7.2	24.8	51.3	82.2	111.8	-17
float_id_7	4031	0.45	9.90	0.58	6.87	0.20	7281	1777	58.25	19.81	6.01	830	2784	18,120	0.5	2.8	22.2	71.0	120.9	171.9	235.5	-30
float_id_8	4155	0.25	11.83	0.57	6.90	0.20	13263	3317	94.37	18.03	4.29	1572	4673	31,275	0.6	2.3	7.3	29.5	77.1	124.0	156.6	-8
float_id_9	5398	0.42	9.67	0.60	4.90	0.17	10667	2210	105.33	16.03	5.34	1343	3744	27,047	0.6	2.3	6.5	19.7	59.8	110.3	147.9	-5
float_id_10	5813	0.39	12.14	0.58	7.30	0.13	13051	1969	80.89	20.54	6.05	1493	4281	29,788	0.6	2.7	10.4	50.0	113.5	166.1	219.4	-14
float_id_11	5410	0.35	12.61	0.51	8.37	0.16	13058	2435	80.82	20.89	6.27	1567	4400	31,055	0.6	2.7	10.7	43.6	91.7	135.3	180.3	-18
float_id_12	5827	0.41	13.18	0.51	7.06	0.21	11106	3028	75.46	18.84	8.05	1370	4059	27,648	0.6	3.0	13.6	44.0	83.6	131.2	187.2	-28
float_id_13	4180	0.27	13.28	0.57	8.69	0.28	11109	4324	57.52	22.32	5.71	1175	4385	24,578	0.5	2.5	18.0	56.8	93.3	129.6	174.8	-28
float_id_14	4546	0.44	10.69	0.46	5.72	0.28	7434	2950	89.28	14.53	7.65	1103	3117	22,794	0.6	2.4	8.3	26.7	47.5	75.9	110.4	-26
float_id_15	3854	0.34	11.41	0.47	5.87	0.23	8671	2587	84.15	15.54	6.27	1157	3337	23,778	0.5	2.4	8.9	31.3	60.8	93.4	129.2	-23
float_id_16	3507	0.33	12.94	0.59	6.80	0.25	7964	2620	47.29	19.95	6.34	832	3168	18,347	0.5	2.7	19.1	45.9	74.7	110.8	158.2	-43
float_id_17	5696	0.38	10.00	0.52	5.59	0.19	12264	2812	125.68	15.95	5.44	1705	4296	33,283	0.7	2.3	6.2	14.6	35.7	66.6	99.1	-4
float_id_18	4973	0.37	9.72	0.59	6.62	0.15	11466	2095	97.62	18.45	4.68	1396	3915	28,000	0.6	2.3	7.3	27.9	78.2	132.4	169.4	-6
float_id_19	5702	0.43	9.50	0.56	6.21	0.21	10432	2804	98.05	17.97	5.80	1344	3833	27,114	0.6	2.4	7.5	27.4	71.0	120.9	161.6	-9
float_id_20	4915	0.44	10.91	0.50	5.76	0.17	9218	1901	90.04	16.00	6.78	1232	3302	25,010	0.6	2.4	8.2	29.8	61.8	99.0	138.4	-19
float_id_21	3592	0.30	10.17	0.48	5.46	0.15	10278	1839	113.68	14.54	4.48	1405	3552	27,988	0.5	2.0	5.5	15.0	35.0	61.6	84.4	-10
float_id_22	5692	0.42	13.14	0.60	7.74	0.22	10530	2918	54.60	22.62	7.73	1101	3887	23,126	0.6	2.6	16.6	44.6	78.5	118.2	169.9	-39

Example Implementation: Down Select Float Functional Group Options

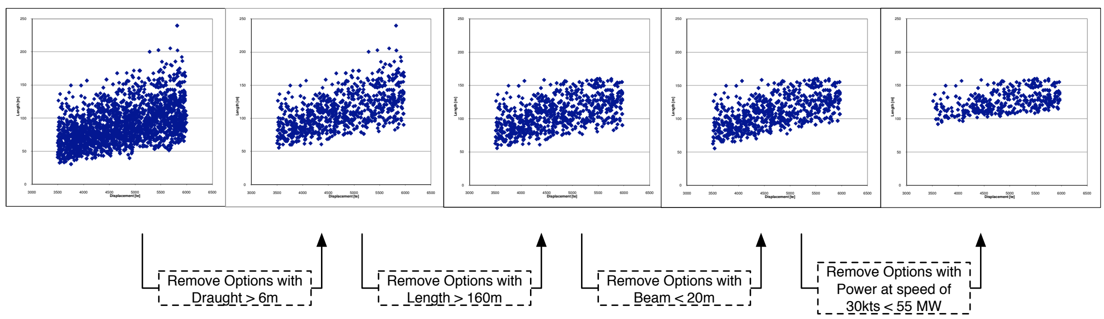
Overview of data flow in the example implementation



Effect of down select on number of remaining Options



Graphical representation of the effect of down select on number of remaining Options

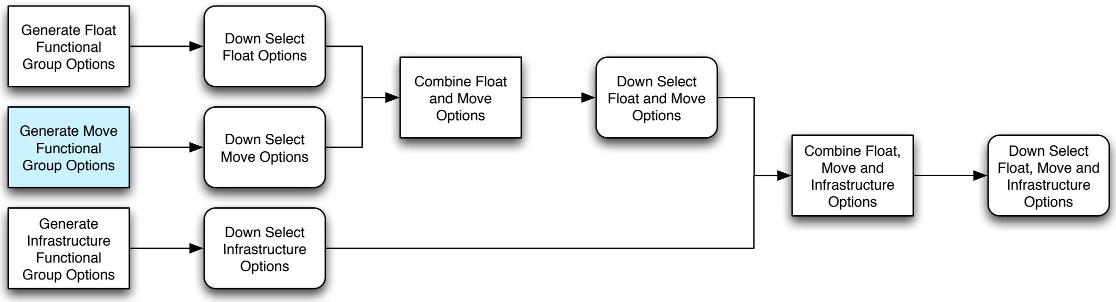


Selection of solution data

	Inputs						From Geo					From Sizing			Power at speed [MW							Sea-keeping
	∇ [te]	ρ [te]	D [m]	Cb [n/a]	KG	vs	Vm [m3]	Vs [m3]	L [m]	B [m]	T [m]	M_float [te]	V_float [m3]	C_float [£k]	10 kts	15 kts	20 kts	25 kts	30 kts	35 kts	40 kts	Sk rank
float_id_4	5132	0.28	10.48	0.45	6.79	0.15	15372	2752	154.93	15.90	4.63	2297	5061	43,420	0.7	2.3	6.0	12.8	25.8	42.9	64.5	-3
float_id_17	5696	0.38	10.00	0.52	5.59	0.19	12264	2812	125.68	15.95	5.44	1705	4296	33,283	0.7	2.3	6.2	14.6	35.7	66.6	99.1	-4
float_id_21	3592	0.30	10.17	0.48	5.46	0.15	10278	1839	113.68	14.54	4.48	1405	3552	27,988	0.5	2.0	5.5	15.0	35.0	61.6	84.4	-10
float_id_25	4396	0.28	11.05	0.48	6.43	0.21	12371	3355	113.73	16.24	4.98	1680	4459	32,959	0.6	2.2	6.2	16.8	39.6	69.8	96.1	-10
float_id_30	4323	0.33	11.02	0.50	5.86	0.10	11743	1344	108.81	15.84	4.98	1545	3796	30,413	0.6	2.1	6.2	18.0	44.2	78.8	105.7	-10
float_id_32	5609	0.26	11.42	0.50	6.78	0.29	15364	6296	125.79	17.35	5.14	2099	5949	40,585	0.7	2.4	6.4	15.3	37.2	68.2	100.6	-4
float_id_37	5883	0.35	9.76	0.55	6.51	0.11	14841	1878	138.16	17.29	4.51	2015	4708	38,602	0.7	2.4	6.4	13.8	32.2	62.6	99.3	1
float_id_43	5540	0.28	11.04	0.48	6.29	0.15	16770	2849	156.81	15.81	4.66	2438	5436	45,934	0.7	2.4	6.1	12.9	26.1	44.4	67.7	-1
float_id_47	4889	0.28	11.35	0.53	5.88	0.21	14016	3668	119.04	16.28	4.73	1830	4950	35,668	0.6	2.2	6.1	15.4	39.9	74.8	106.0	-5
float_id_48	4463	0.30	10.04	0.59	5.91	0.17	12445	2464	112.90	16.61	4.06	1560	4254	30,879	0.6	2.2	6.2	16.7	48.8	93.6	124.4	-3
float_id_51	4823	0.32	11.15	0.48	7.17	0.11	13606	1674	115.12	17.42	4.99	1825	4347	35,295	0.6	2.3	6.5	17.3	41.9	74.4	102.9	-8
float_id_54	4319	0.28	10.90	0.55	6.23	0.14	13494	2184	115.50	16.51	4.12	1716	4447	33,541	0.6	2.1	6.1	16.0	43.0	80.8	110.0	-4
float_id_62	5938	0.30	11.11	0.57	6.27	0.26	14656	5081	114.73	17.83	5.14	1872	5466	36,602	0.7	2.4	6.8	17.9	50.9	97.4	134.9	-2
float_id_66	4475	0.26	12.48	0.47	8.12	0.12	15419	2051	108.96	18.29	4.73	1982	4897	38,139	0.6	2.3	6.8	19.9	47.0	82.4	108.6	-9
float_id_69	5435	0.36	10.11	0.48	6.74	0.13	12991	1927	128.20	16.90	5.23	1853	4256	35,713	0.7	2.3	6.3	14.7	34.3	61.5	91.4	-5
float_id_77	4326	0.28	10.41	0.46	5.45	0.26	11553	4137	130.00	14.40	4.99	1684	4450	33,010	0.6	2.1	5.4	12.6	27.8	48.2	71.7	-8
float_id_82	4982	0.28	12.57	0.53	6.42	0.14	15051	2521	108.47	17.29	5.01	1888	4922	36,611	0.6	2.3	6.6	19.4	51.5	94.0	124.8	-7
float_id_94	5878	0.27	12.30	0.48	7.32	0.18	17795	3947	133.93	17.69	5.22	2462	5969	46,578	0.7	2.4	6.5	14.6	33.5	60.2	91.5	-3
float_id_100	5269	0.31	10.95	0.52	6.83	0.17	14144	2901	117.43	17.61	4.92	1866	4790	36,181	0.6	2.3	6.5	16.8	43.5	80.3	112.7	-5
float_id_109	5784	0.33	10.37	0.51	6.89	0.21	13671	3726	121.04	17.82	5.25	1865	4879	36,208	0.7	2.4	6.7	16.5	41.6	76.9	110.9	-4
float_id_111	4605	0.30	10.14	0.57	6.04	0.11	13874	1662	127.49	16.32	3.87	1793	4411	34,793	0.6	2.2	5.9	13.9	35.2	68.3	101.3	-1
float_id_120	5061	0.35	9.59	0.49	5.70	0.10	13022	1494	148.15	15.11	4.60	1904	4155	36,497	0.7	2.3	5.9	12.6	26.2	45.3	69.6	-2

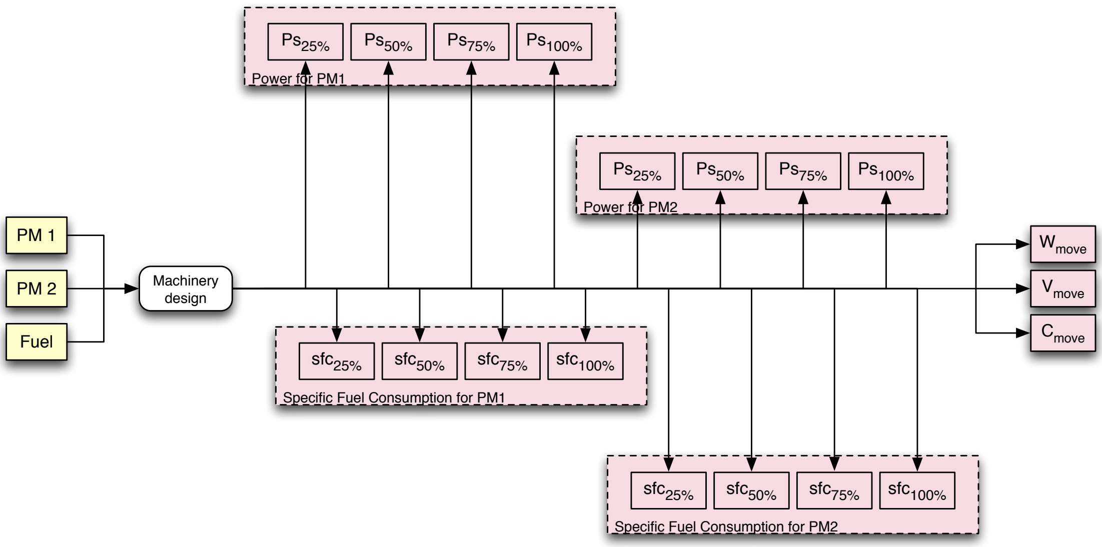
Example Implementation: Generating Move Functional Group Options

Overview of data flow in the example implementation



Additional explanation of step

Key: Input | Output | Intermediate step

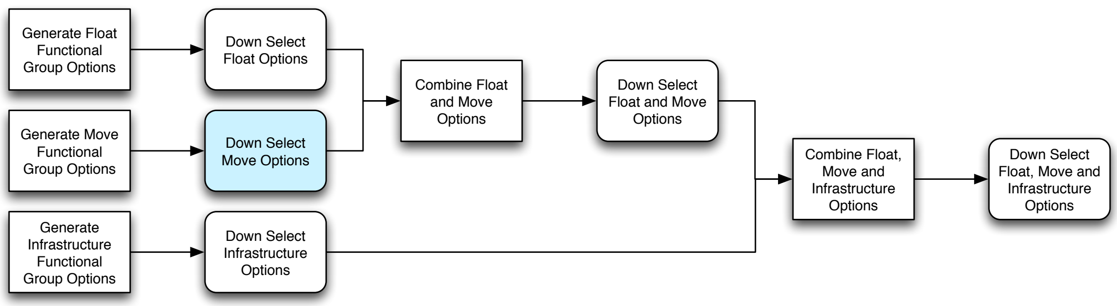


Selection of solution data

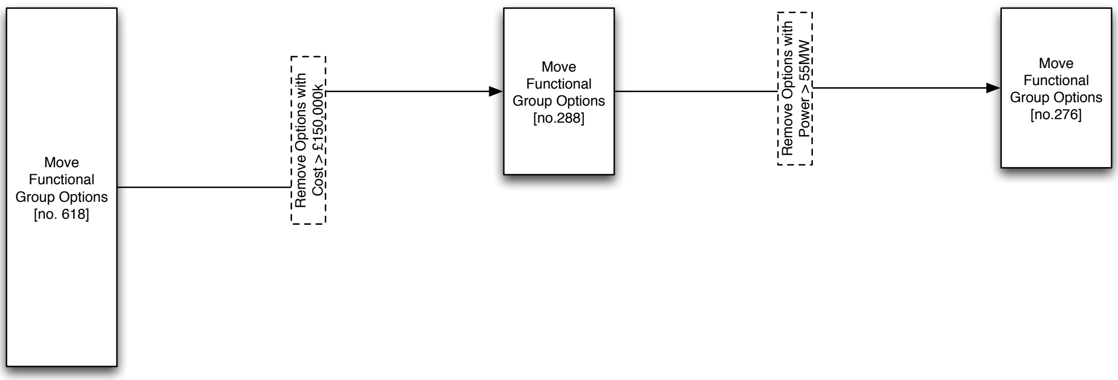
	Inputs			Sizing			Prime mover power at % of MCR												Prime m			
	PM1	PM 2	Fuel [te]	M_move [te]	V_move [m3]	C_move [£k]	PM1 25%	PM1 50%	PM1 75%	PM1 100%	PM2 25%	PM1 50%	PM2 75%	PM2 100%	PMall 25%	PMall 50%	PMall 75%	PMall 100%	PM1 25%	PM1 50%	PM1 75%	PM1 100%
move_id_1	no engine	LM500	300	427	1028	12140	0.0	0.0	0.0	0.0	0.7	1.4	2.1	2.9	0.7	1.4	2.1	2.9	0.00	0.00	0.00	0.00
move_id_2	LM500	LM500	300	524	1516	21760	0.7	1.4	2.1	2.9	0.7	1.4	2.1	2.9	1.4	2.9	4.3	5.7	0.80	1.27	1.66	2.01
move_id_3	no engine	12PA6B	300	369	743	4025	0.0	0.0	0.0	0.0	0.8	1.5	2.3	3.1	0.8	1.5	2.3	3.1	0.00	0.00	0.00	0.00
move_id_4	LM500	12PA6B	300	467	1230	13645	0.7	1.4	2.1	2.9	0.8	1.5	2.3	3.1	1.5	3.0	4.5	6.0	0.80	1.27	1.66	2.01
move_id_5	12PA6B	12PA6B	300	410	945	5530	0.8	1.5	2.3	3.1	0.8	1.5	2.3	3.1	1.5	3.1	4.6	6.2	0.33	0.61	0.88	1.14
move_id_6	no engine	16PA6B	300	378	787	4124	0.0	0.0	0.0	0.0	1.0	2.1	3.1	4.1	1.0	2.1	3.1	4.1	0.00	0.00	0.00	0.00
move_id_7	LM500	16PA6B	300	476	1275	13744	0.7	1.4	2.1	2.9	1.0	2.1	3.1	4.1	1.7	3.5	5.2	7.0	0.80	1.27	1.66	2.01
move_id_8	12PA6B	16PA6B	300	419	989	5629	0.8	1.5	2.3	3.1	1.0	2.1	3.1	4.1	1.8	3.6	5.4	7.2	0.33	0.61	0.88	1.14
move_id_9	16PA6B	16PA6B	300	428	1033	5728	1.0	2.1	3.1	4.1	1.0	2.1	3.1	4.1	2.1	4.1	6.2	8.3	0.45	0.84	1.21	1.56
move_id_10	no engine	20PA6B	300	387	830	4207	0.0	0.0	0.0	0.0	1.3	2.6	3.9	5.2	1.3	2.6	3.9	5.2	0.00	0.00	0.00	0.00
move_id_11	LM500	20PA6B	300	485	1318	13827	0.7	1.4	2.1	2.9	1.3	2.6	3.9	5.2	2.0	4.0	6.0	8.0	0.80	1.27	1.66	2.01
move_id_12	12PA6B	20PA6B	300	427	1032	5712	0.8	1.5	2.3	3.1	1.3	2.6	3.9	5.2	2.1	4.1	6.2	8.3	0.33	0.61	0.88	1.14
move_id_13	16PA6B	20PA6B	300	436	1077	5811	1.0	2.1	3.1	4.1	1.3	2.6	3.9	5.2	2.3	4.6	7.0	9.3	0.45	0.84	1.21	1.56
move_id_14	20PA6B	20PA6B	300	445	1120	5895	1.3	2.6	3.9	5.2	1.3	2.6	3.9	5.2	2.6	5.2	7.7	10.3	0.57	1.07	1.54	2.00
move_id_15	no engine	LM1600	300	461	1203	14756	0.0	0.0	0.0	0.0	2.4	4.7	7.1	9.5	2.4	4.7	7.1	9.5	0.00	0.00	0.00	0.00
move_id_16	LM500	LM1600	300	559	1691	24376	0.7	1.4	2.1	2.9	2.4	4.7	7.1	9.5	3.1	6.2	9.3	12.4	0.80	1.27	1.66	2.01
move_id_17	12PA6B	LM1600	300	502	1405	16261	0.8	1.5	2.3	3.1	2.4	4.7	7.1	9.5	3.1	6.3	9.4	12.6	0.33	0.61	0.88	1.14
move_id_18	16PA6B	LM1600	300	511	1449	16360	1.0	2.1	3.1	4.1	2.4	4.7	7.1	9.5	3.4	6.8	10.2	13.6	0.45	0.84	1.21	1.56
move_id_19	20PA6B	LM1600	300	519	1493	16443	1.3	2.6	3.9	5.2	2.4	4.7	7.1	9.5	3.7	7.3	11.0	14.7	0.57	1.07	1.54	2.00
move_id_20	LM1600	LM1600	300	594	1865	26992	2.4	4.7	7.1	9.5	2.4	4.7	7.1	9.5	4.7	9.5	14.2	19.0	3.35	5.31	6.96	8.42
move_id_21	no engine	Spey	300	454	1167	12689	0.0	0.0	0.0	0.0	3.1	6.2	9.3	12.4	3.1	6.2	9.3	12.4	0.00	0.00	0.00	0.00
move_id_22	LM500	Spey	300	552	1655	22309	0.7	1.4	2.1	2.9	3.1	6.2	9.3	12.4	3.8	7.6	11.5	15.3	0.80	1.27	1.66	2.01

Example Implementation: Down Select Move Functional Group Options

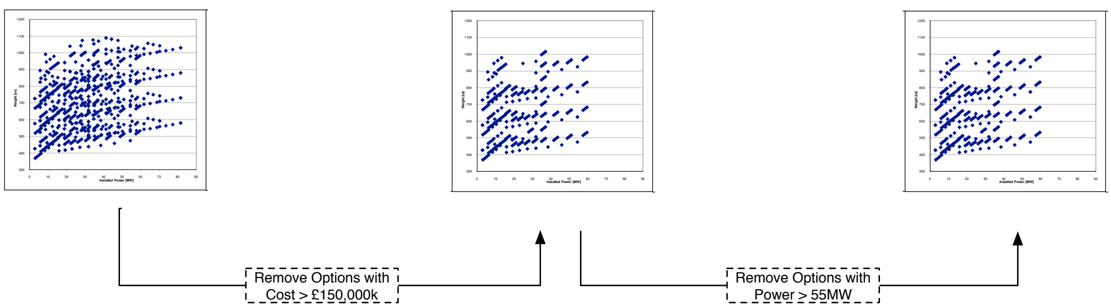
Overview of data flow in the example implementation



Effect of down select on number of remaining Options



Graphical representation of the effect of down select on number of remaining Options

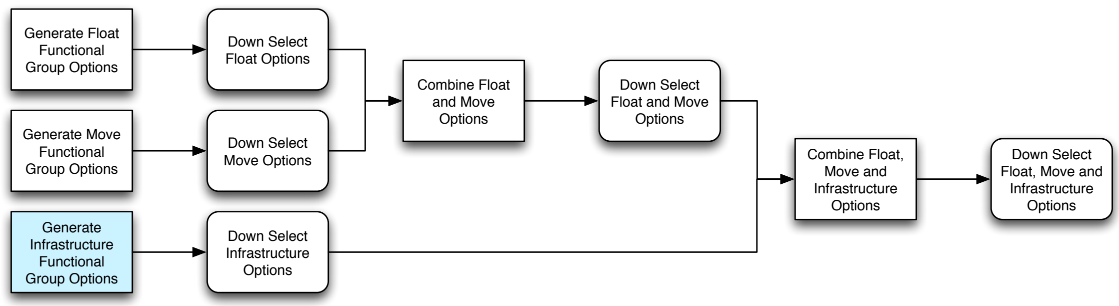


Selection of solution data

		Inputs			Sizing			Prime mover power at % of MCR													
		PM1	PM 2	Fuel [te]	M_move [te]	V_move [m3]	C_move [£k]	PM1 25%	PM1 50%	PM1 75%	PM1 100%	PM2 25%	PM1 50%	PM2 75%	PM2 100%	PMall 25%	PMall 50%	PMall 75%	PMall 100%	PM1 25%	PM1 50%
1	move_id_1	no engine	LM500	300	427	1028	12140	0.0	0.0	0.0	0.0	0.7	1.4	2.1	2.9	0.7	1.4	2.1	2.9	0.00	0.00
1	move_id_3	no engine	12PA6B	300	369	743	4025	0.0	0.0	0.0	0.0	0.8	1.5	2.3	3.1	0.8	1.5	2.3	3.1	0.00	0.00
1	move_id_4	LM500	12PA6B	300	467	1230	13645	0.7	1.4	2.1	2.9	0.8	1.5	2.3	3.1	1.5	3.0	4.5	6.0	0.80	1.27
1	move_id_5	12PA6B	12PA6B	300	410	945	5530	0.8	1.5	2.3	3.1	0.8	1.5	2.3	3.1	1.5	3.1	4.6	6.2	0.33	0.61
1	move_id_6	no engine	16PA6B	300	378	787	4124	0.0	0.0	0.0	0.0	1.0	2.1	3.1	4.1	1.0	2.1	3.1	4.1	0.00	0.00
1	move_id_7	LM500	16PA6B	300	476	1275	13744	0.7	1.4	2.1	2.9	1.0	2.1	3.1	4.1	1.7	3.5	5.2	7.0	0.80	1.27
1	move_id_8	12PA6B	16PA6B	300	419	989	5629	0.8	1.5	2.3	3.1	1.0	2.1	3.1	4.1	1.8	3.6	5.4	7.2	0.33	0.61
1	move_id_9	16PA6B	16PA6B	300	428	1033	5728	1.0	2.1	3.1	4.1	1.0	2.1	3.1	4.1	2.1	4.1	6.2	8.3	0.45	0.84
1	move_id_10	no engine	20PA6B	300	387	830	4207	0.0	0.0	0.0	0.0	1.3	2.6	3.9	5.2	1.3	2.6	3.9	5.2	0.00	0.00
1	move_id_11	LM500	20PA6B	300	485	1318	13827	0.7	1.4	2.1	2.9	1.3	2.6	3.9	5.2	2.0	4.0	6.0	8.0	0.80	1.27
1	move_id_12	12PA6B	20PA6B	300	427	1032	5712	0.8	1.5	2.3	3.1	1.3	2.6	3.9	5.2	2.1	4.1	6.2	8.3	0.33	0.61
1	move_id_13	16PA6B	20PA6B	300	436	1077	5811	1.0	2.1	3.1	4.1	1.3	2.6	3.9	5.2	2.3	4.6	7.0	9.3	0.45	0.84
1	move_id_14	20PA6B	20PA6B	300	445	1120	5895	1.3	2.6	3.9	5.2	1.3	2.6	3.9	5.2	2.6	5.2	7.7	10.3	0.57	1.07
1	move_id_15	no engine	LM1600	300	461	1203	14756	0.0	0.0	0.0	0.0	2.4	4.7	7.1	9.5	2.4	4.7	7.1	9.5	0.00	0.00
1	move_id_21	no engine	Spey	300	454	1167	12689	0.0	0.0	0.0	0.0	3.1	6.2	9.3	12.4	3.1	6.2	9.3	12.4	0.00	0.00
1	move_id_23	12PA6B	Spey	300	495	1369	14194	0.8	1.5	2.3	3.1	3.1	6.2	9.3	12.4	3.9	7.8	11.6	15.5	0.33	0.61
1	move_id_24	16PA6B	Spey	300	504	1413	14293	1.0	2.1	3.1	4.1	3.1	6.2	9.3	12.4	4.1	8.3	12.4	16.5	0.45	0.84
1	move_id_25	20PA6B	Spey	300	512	1457	14377	1.3	2.6	3.9	5.2	3.1	6.2	9.3	12.4	4.4	8.8	13.2	17.6	0.57	1.07
1	move_id_28	no engine	WR-21 DD	300	447	1130	9565	0.0	0.0	0.0	0.0	4.0	8.0	11.9	15.9	4.0	8.0	11.9	15.9	0.00	0.00
1	move_id_30	12PA6B	WR-21 DD	300	487	1333	11070	0.8	1.5	2.3	3.1	4.0	8.0	11.9	15.9	4.8	9.5	14.3	19.0	0.33	0.61
1	move_id_31	16PA6B	WR-21 DD	300	496	1377	11169	1.0	2.1	3.1	4.1	4.0	8.0	11.9	15.9	5.0	10.0	15.0	20.1	0.45	0.84
1	move_id_32	20PA6B	WR-21 DD	300	505	1420	11252	1.3	2.6	3.9	5.2	4.0	8.0	11.9	15.9	5.3	10.5	15.8	21.1	0.57	1.07

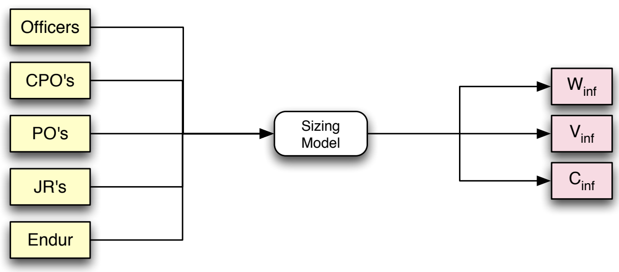
Example Implementation: Generating Infrastructure Functional Group Options

Overview of data flow in the example implementation



Additional explanation of step

Key: Input Output Intermediate step

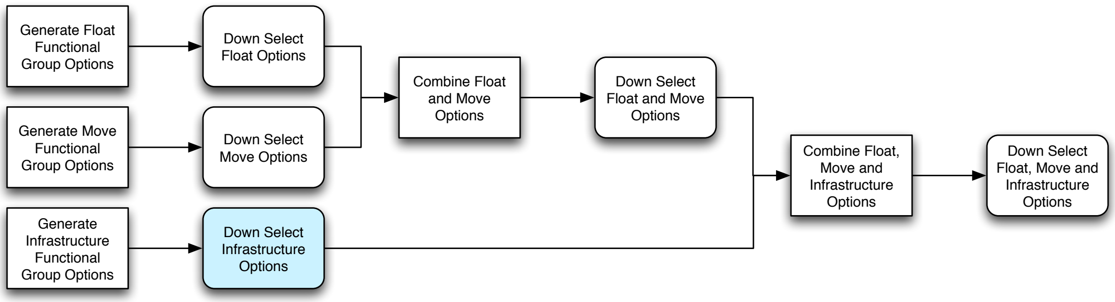


Selection of solution data

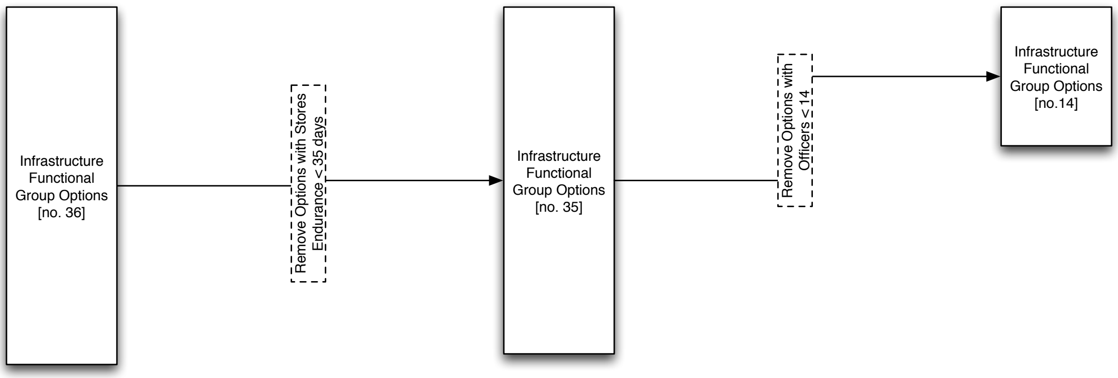
	Inputs					From Sizing		
	Officers	Displacement	POs	JRs	Stores Endura	W_inf	V_inf	C_inf
inf_id_1	5	10	10	50	20	690	2971	53074
inf_id_2	8	15	15	75	20	719	3420	54595
inf_id_3	9	18	18	90	20	735	3669	55442
inf_id_4	10	20	20	100	20	746	3844	56034
inf_id_5	12	24	24	120	20	768	4193	57218
inf_id_6	15	29	29	145	20	797	4642	58739
inf_id_7	15	31	31	153	20	805	4771	59176
inf_id_8	17	34	34	170	20	824	5066	60178
inf_id_9	19	38	38	190	20	846	5416	61362
inf_id_10	5	10	10	50	30	693	2976	53243
inf_id_11	8	15	15	75	30	724	3428	54850
inf_id_12	9	18	18	90	30	741	3679	55746
inf_id_13	10	20	20	100	30	752	3855	56372
inf_id_14	12	24	24	120	30	776	4206	57624
inf_id_15	15	29	29	145	30	806	4658	59230
inf_id_16	15	31	31	153	30	815	4788	59695

Example Implementation: Down Select Infrastructure Functional Group Options

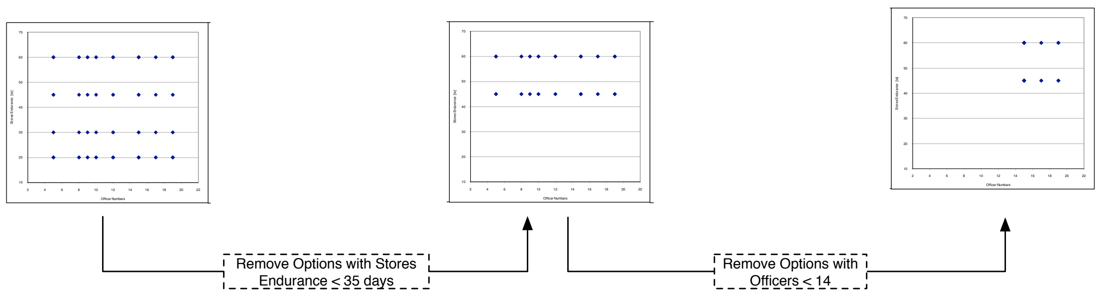
Overview of data flow in the example implementation



Effect of down select on number of remaining Options



Graphical representation of the effect of down select on number of remaining Options

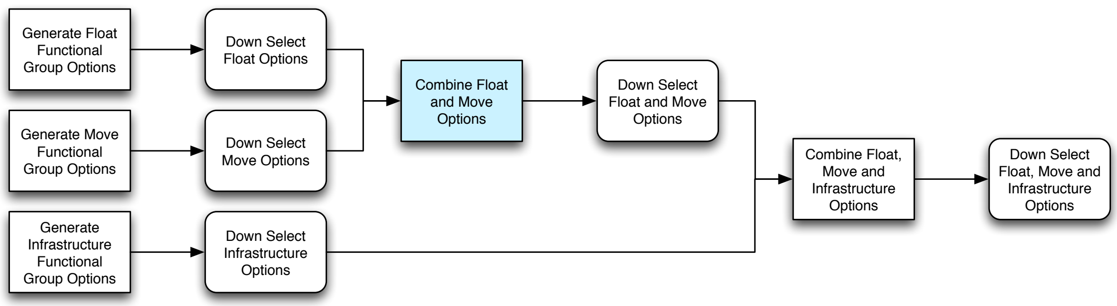


Selection of solution data

		Inputs					From Sizing		
		Officers	Displacement	POs	JRs	Stores Endura	W_inf	V_inf	C_inf
1	inf_id_24	15	29	29	145	45	820	4682	59968
1	inf_id_25	15	31	31	153	45	829	4814	60473
1	inf_id_26	17	34	34	170	45	851	5113	61615
1	inf_id_27	19	38	38	190	45	876	5468	62968
1	inf_id_33	15	29	29	145	60	834	4706	60705
1	inf_id_34	15	31	31	153	60	844	4839	61251
1	inf_id_35	17	34	34	170	60	867	5141	62478
1	inf_id_36	19	38	38	190	60	894	5499	63932

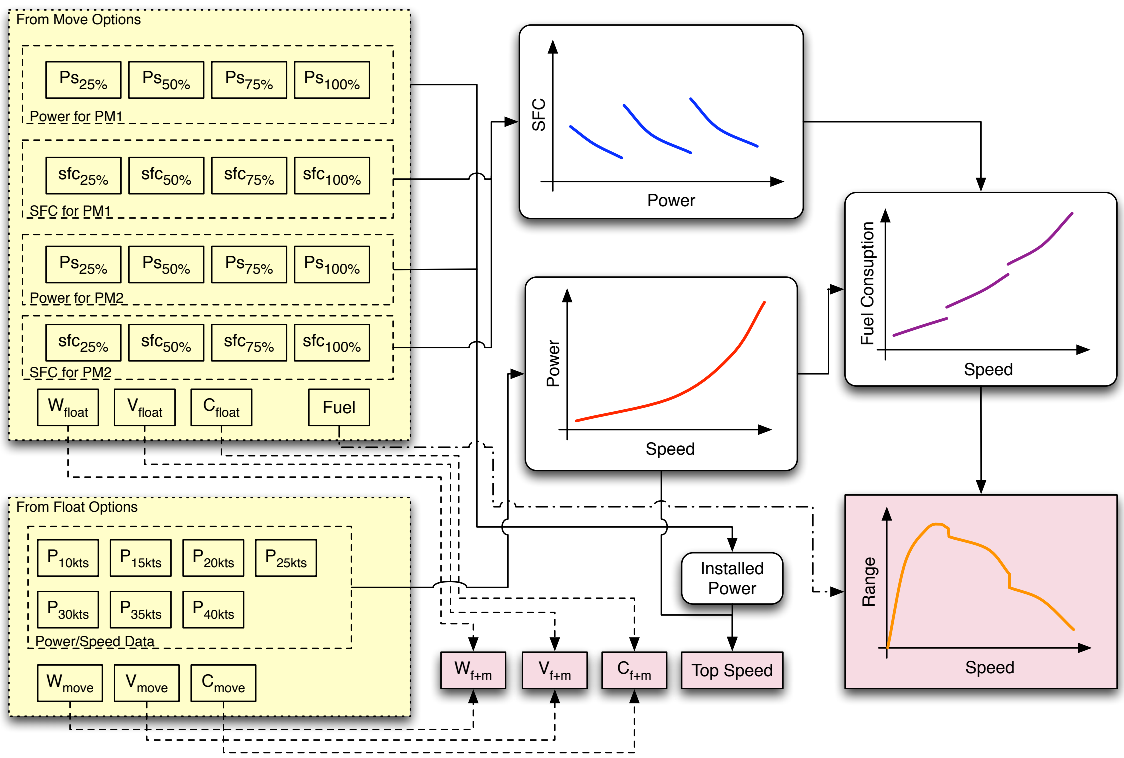
Example Implementation: Combine Float and Move Functional Group Options

Overview of data flow in the example implementation



Additional explanation of step

Key: Input Output Intermediate step

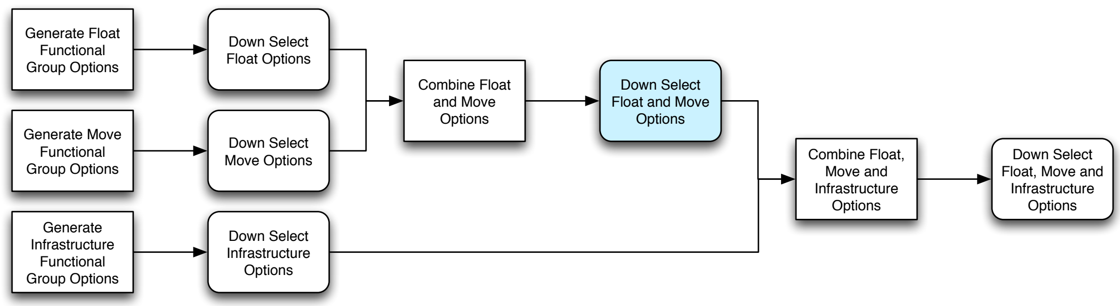


Selection of solution data

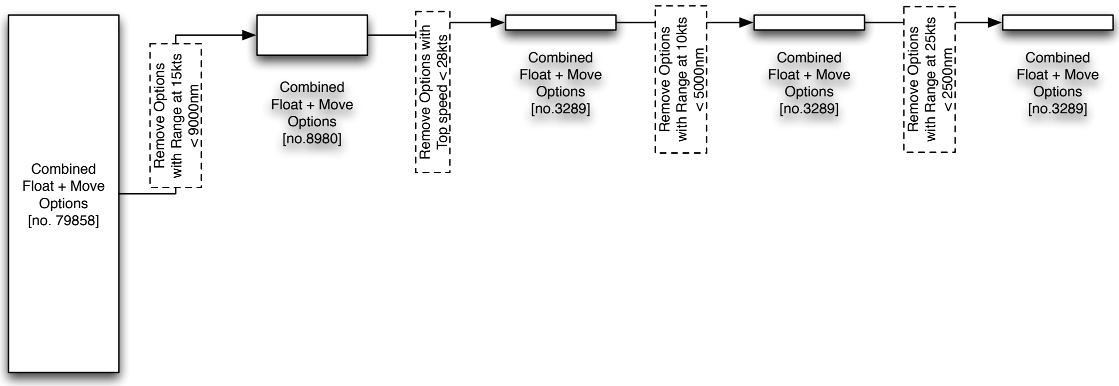
		Top speed	From Sizing			Minimum Fuel Consumption per hour [te/hr]							Range at speed given below [nm]						
			Mf+m [te]	Vf+m [m3]	Cf+m [£k]	10 kts	15 kts	20 kts	25 kts	30 kts	35 kts	40 kts	10 kts	15 kts	20 kts	25 kts	30 kts	35 kts	40 kts
float_id_4	move_id_1	15.8	2723	6089	55560	0.83	1.74	2.03	2.03	2.03	2.03	2.03	530	73	0	0	0	0	0
float_id_4	move_id_3	16.1	2666	5804	47445	0.33	0.88	1.14	1.14	1.14	1.14	1.14	1320	145	0	0	0	0	0
float_id_4	move_id_4	19.5	2764	6292	57065	0.33	0.88	1.14	1.14	1.14	1.14	1.14	1320	145	0	0	0	0	0
float_id_4	move_id_5	19.7	2707	6006	48950	0.33	0.88	1.14	1.14	1.14	1.14	1.14	1320	145	0	0	0	0	0
float_id_4	move_id_6	17.5	2675	5848	47544	0.46	0.93	1.57	1.57	1.57	1.57	1.57	962	137	0	0	0	0	0
float_id_4	move_id_7	20.4	2773	6336	57164	0.46	0.93	1.57	1.57	1.57	1.57	1.57	962	137	32	0	0	0	0
float_id_4	move_id_8	20.6	2716	6050	49049	0.33	0.88	1.14	1.14	1.14	1.14	1.14	1320	145	43	0	0	0	0
float_id_4	move_id_9	21.4	2724	6094	49148	0.46	0.93	1.57	1.57	1.57	1.57	1.57	962	137	32	0	0	0	0
float_id_4	move_id_10	18.7	2684	5891	47627	0.58	0.97	2.01	2.01	2.01	2.01	2.01	752	131	0	0	0	0	0
float_id_4	move_id_11	21.2	2781	6379	57247	0.58	0.97	2.01	2.01	2.01	2.01	2.01	752	131	25	0	0	0	0
float_id_4	move_id_12	21.4	2724	6093	49132	0.33	0.88	1.14	1.14	1.14	1.14	1.14	1320	145	43	0	0	0	0
float_id_4	move_id_13	22.2	2733	6138	49231	0.46	0.93	1.57	1.57	1.57	1.57	1.57	962	137	32	0	0	0	0
float_id_4	move_id_14	22.9	2742	6181	49315	0.58	0.97	2.01	2.01	2.01	2.01	2.01	752	131	25	0	0	0	0
float_id_4	move_id_15	22.3	2758	6264	58176	3.48	3.48	6.09	8.54	8.54	8.54	8.54	126	37	8	0	0	0	0
float_id_4	move_id_21	24.2	2751	6228	56109	4.93	4.93	7.18	12.09	12.09	12.09	12.09	89	26	7	0	0	0	0
float_id_4	move_id_23	25.9	2792	6430	57614	0.33	0.88	1.14	1.14	1.14	1.14	1.14	1320	145	43	21	0	0	0
float_id_4	move_id_24	26.4	2800	6475	57714	0.46	0.93	1.57	1.57	1.57	1.57	1.57	962	137	32	15	0	0	0
float_id_4	move_id_25	26.9	2809	6518	57797	0.58	0.97	2.01	2.01	2.01	2.01	2.01	752	131	25	12	0	0	0
float_id_4	move_id_28	26.1	2744	6192	52985	4.17	4.17	5.42	9.52	11.45	11.45	11.45	720	1080	1106	788	0	0	0
float_id_4	move_id_30	27.5	2784	6394	54490	0.33	0.88	1.14	1.14	1.14	1.14	1.14	9007	5097	5244	6555	0	0	0
float_id_4	move_id_31	28.0	2793	6438	54589	0.46	0.93	1.57	1.57	1.57	1.57	1.57	6563	4838	3822	4777	0	0	0
float_id_4	move_id_32	28.4	2802	6481	54672	0.58	0.97	2.01	2.01	2.01	2.01	2.01	5135	4624	2990	3737	0	0	0

Example Implementation: Down Select Combined Float-Move Functional Group Options

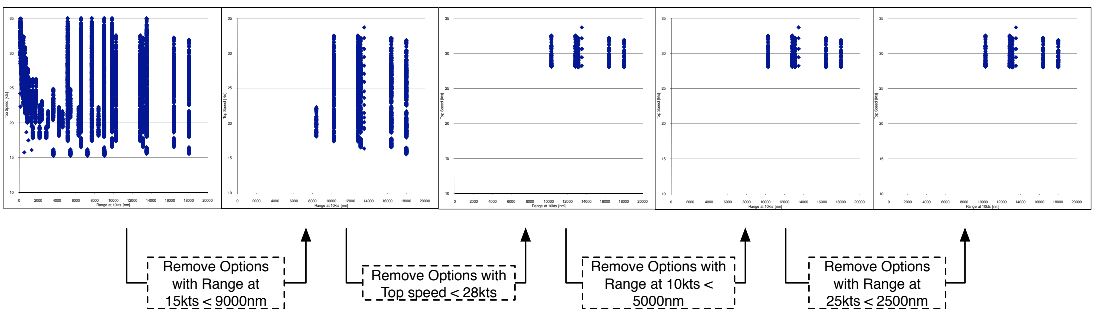
Overview of data flow in the example implementation



Effect of down select on number of remaining Options



Graphical representation of the effect of down select on number of remaining Options

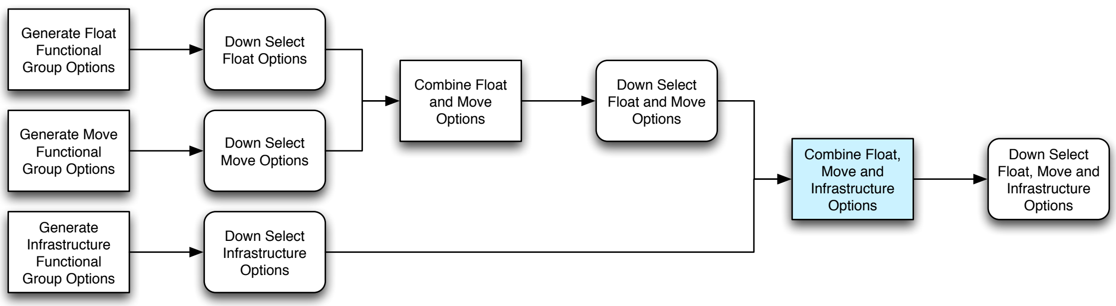


Selection of solution data

		Top speed	From Sizing			Minimum Fuel Consumption per hour [te/hr]							Range at speed given below [nm]						
			Mf+m [te]	Vf+m [m3]	Cf+m [£k]	10 kts	15 kts	20 kts	25 kts	30 kts	35 kts	40 kts	10 kts	15 kts	20 kts	25 kts	30 kts	35 kts	40 kts
float_id_4	move_id_186	28.4	3102	6877	54672	0.584234	0.973197	2.006737	2.006737	2.006737	2.006737	2.006737	10269.85	9247.867	5979.856	7474.82	0	0	0
float_id_4	move_id_201	28.9	3055	6642	54708	0.333084	0.882898	1.144081	1.144081	1.144081	1.144081	1.144081	18013.48	10193.7	10488.77	13110.96	0	0	0
float_id_4	move_id_203	29.7	3072	6730	54891	0.584234	0.973197	2.006737	2.006737	2.006737	2.006737	2.006737	10269.85	9247.867	5979.856	7474.82	0	0	0
float_id_4	move_id_212	30.6	3071	6722	55073	0.457074	0.930194	1.569963	1.569963	1.569963	1.569963	1.569963	13126.99	9675.401	7643.491	9554.364	11465.24	0	0
float_id_4	move_id_222	31.7	3072	6726	55245	0.333084	0.882898	1.144081	1.144081	1.144081	1.144081	1.144081	18013.48	10193.7	10488.77	13110.96	15733.15	0	0
float_id_4	move_id_224	32.4	3089	6813	55428	0.584234	0.973197	2.006737	2.006737	2.006737	2.006737	2.006737	10269.85	9247.867	5979.856	7474.82	8969.785	0	0
float_id_4	move_id_263	28.4	3252	7075	54672	0.584234	0.973197	2.006737	2.006737	2.006737	2.006737	2.006737	12837.31	11559.83	7474.82	9343.526	0	0	0
float_id_4	move_id_278	28.9	3205	6840	54708	0.333084	0.882898	1.144081	1.144081	1.144081	1.144081	1.144081	22516.86	12742.13	13110.96	16388.7	0	0	0
float_id_4	move_id_280	29.7	3222	6927	54891	0.584234	0.973197	2.006737	2.006737	2.006737	2.006737	2.006737	12837.31	11559.83	7474.82	9343.526	0	0	0
float_id_4	move_id_289	30.6	3221	6920	55073	0.457074	0.930194	1.569963	1.569963	1.569963	1.569963	1.569963	16408.74	12094.25	9554.364	11942.95	14331.55	0	0
float_id_4	move_id_299	31.7	3222	6923	55245	0.333084	0.882898	1.144081	1.144081	1.144081	1.144081	1.144081	22516.86	12742.13	13110.96	16388.7	19666.44	0	0
float_id_4	move_id_301	32.4	3239	7011	55428	0.584234	0.973197	2.006737	2.006737	2.006737	2.006737	2.006737	12837.31	11559.83	7474.82	9343.526	11212.23	0	0
float_id_17	move_id_213	28.1	2487	6000	45020	0.584234	0.955403	2.006737	2.006737	2.006737	2.006737	2.006737	10269.85	9420.108	5979.856	7474.82	0	0	0
float_id_17	move_id_223	29.0	2488	6005	45208	0.457074	0.912792	1.569963	1.569963	1.569963	1.569963	1.569963	13126.99	9859.854	7643.491	9554.364	0	0	0
float_id_17	move_id_290	28.1	2637	6198	45020	0.584234	0.955403	2.006737	2.006737	2.006737	2.006737	2.006737	12837.31	11775.13	7474.82	9343.526	0	0	0
float_id_17	move_id_299	28.7	2629	6158	45109	0.333084	0.86599	1.144081	1.144081	1.144081	1.144081	1.144081	22516.86	12990.91	13110.96	16388.7	0	0	0
float_id_17	move_id_301	29.2	2647	6246	45291	0.584234	0.955403	2.006737	2.006737	2.006737	2.006737	2.006737	12837.31	11775.13	7474.82	9343.526	0	0	0
float_id_21	move_id_145	29.4	2030	5019	39813	0.333084	0.745736	1.144081	1.144081	1.144081	1.144081	1.144081	13510.11	9051.463	7866.574	9833.218	0	0	0
float_id_21	move_id_212	28.5	2179	5213	39641	0.457074	0.789028	1.569963	1.569963	1.569963	1.569963	1.569963	13126.99	11406.43	7643.491	9554.364	0	0	0
float_id_21	move_id_222	29.4	2180	5217	39813	0.333084	0.745736	1.144081	1.144081	1.144081	1.144081	1.144081	18013.48	12068.62	10488.77	13110.96	0	0	0
float_id_21	move_id_224	30.0	2198	5305	39995	0.584234	0.828846	2.006737	2.006737	2.006737	2.006737	2.006737	10269.85	10858.47	5979.856	7474.82	0	0	0
float_id_21	move_id_288	28.2	2321	5367	39542	0.333084	0.745736	1.144081	1.144081	1.144081	1.144081	1.144081	22516.86	15085.77	13110.96	16388.7	0	0	0

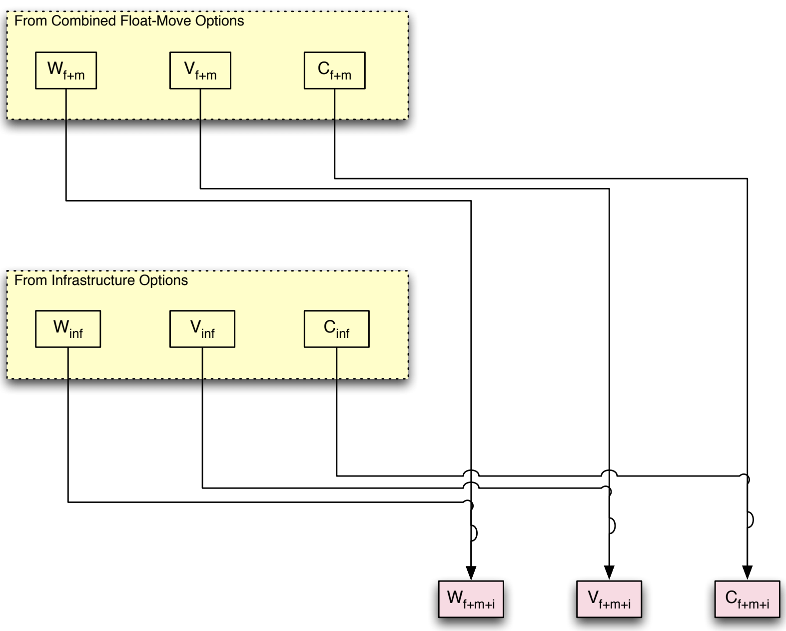
Example Implementation: Combine Float-Move and Infrastructure Functional Group Opt's

Overview of data flow in the example implementation



Additional explanation of step

Key: Input | Output | Intermediate step

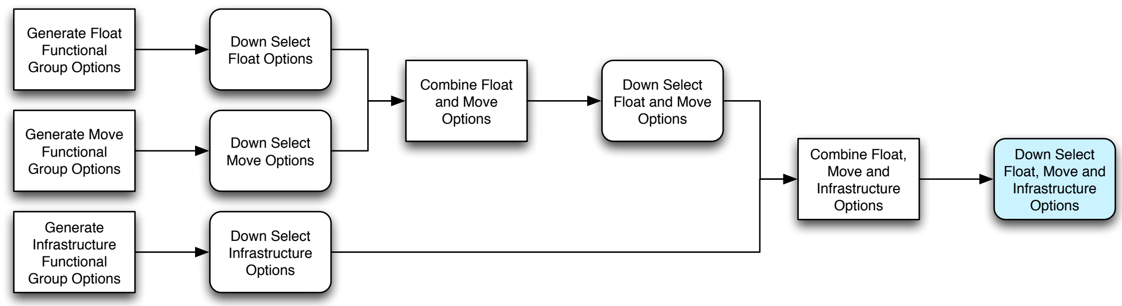


Selection of solution data

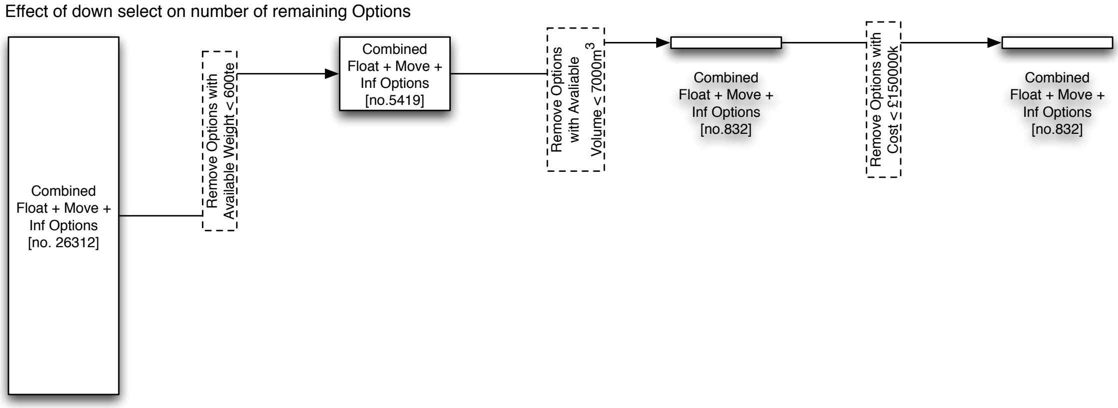
	Inputs	From Geo	Sea-keeping		Inputs			Top speed	Range at speed given below [nm]				Inputs		Total Ship Characteristics		
	∇ [te]	L [m]	Sk rank		PM1	PM2	Fuel [te]		15 kts	20 kts	25 kts		Officers	Stores Endurance	∇-Mf+m+i [te]	V-Vf+m+i [m3]	Cf+m+i [£k]
float_id_4	5132	154.9326	-3.17	move_id_186	20PA6B	WR-21 DD	600	28.4	9248	5980	7475	inf_id_24	15	45	1210	6565	114,640
float_id_4	5132	154.9326	-3.17	move_id_186	20PA6B	WR-21 DD	600	28.4	9248	5980	7475	inf_id_25	15	45	1201	6434	115,145
float_id_4	5132	154.9326	-3.17	move_id_186	20PA6B	WR-21 DD	600	28.4	9248	5980	7475	inf_id_26	17	45	1179	6135	116,287
float_id_4	5132	154.9326	-3.17	move_id_186	20PA6B	WR-21 DD	600	28.4	9248	5980	7475	inf_id_27	19	45	1154	5780	117,640
float_id_4	5132	154.9326	-3.17	move_id_186	20PA6B	WR-21 DD	600	28.4	9248	5980	7475	inf_id_33	15	60	1196	6541	115,377
float_id_4	5132	154.9326	-3.17	move_id_186	20PA6B	WR-21 DD	600	28.4	9248	5980	7475	inf_id_34	15	60	1186	6409	115,923
float_id_4	5132	154.9326	-3.17	move_id_186	20PA6B	WR-21 DD	600	28.4	9248	5980	7475	inf_id_35	17	60	1163	6107	117,150
float_id_4	5132	154.9326	-3.17	move_id_186	20PA6B	WR-21 DD	600	28.4	9248	5980	7475	inf_id_36	19	60	1136	5748	118,604
float_id_4	5132	154.9326	-3.17	move_id_194	20PA6B	LM2500	600	28.4	9248	5980	7475	inf_id_24	15	45	1244	6736	114,587
float_id_4	5132	154.9326	-3.17	move_id_194	20PA6B	LM2500	600	28.4	9248	5980	7475	inf_id_25	15	45	1235	6605	115,092
float_id_4	5132	154.9326	-3.17	move_id_194	20PA6B	LM2500	600	28.4	9248	5980	7475	inf_id_26	17	45	1213	6305	116,234
float_id_4	5132	154.9326	-3.17	move_id_194	20PA6B	LM2500	600	28.4	9248	5980	7475	inf_id_27	19	45	1188	5950	117,587
float_id_4	5132	154.9326	-3.17	move_id_194	20PA6B	LM2500	600	28.4	9248	5980	7475	inf_id_33	15	60	1230	6712	115,324
float_id_4	5132	154.9326	-3.17	move_id_194	20PA6B	LM2500	600	28.4	9248	5980	7475	inf_id_34	15	60	1220	6579	115,870
float_id_4	5132	154.9326	-3.17	move_id_194	20PA6B	LM2500	600	28.4	9248	5980	7475	inf_id_35	17	60	1197	6277	117,097
float_id_4	5132	154.9326	-3.17	move_id_194	20PA6B	LM2500	600	28.4	9248	5980	7475	inf_id_36	19	60	1170	5919	118,551
float_id_4	5132	154.9326	-3.17	move_id_201	12PA6B	LM2500+	600	28.9	10194	10489	13111	inf_id_24	15	45	1257	6800	114,676
float_id_4	5132	154.9326	-3.17	move_id_201	12PA6B	LM2500+	600	28.9	10194	10489	13111	inf_id_25	15	45	1248	6669	115,181
float_id_4	5132	154.9326	-3.17	move_id_201	12PA6B	LM2500+	600	28.9	10194	10489	13111	inf_id_26	17	45	1226	6370	116,323
float_id_4	5132	154.9326	-3.17	move_id_201	12PA6B	LM2500+	600	28.9	10194	10489	13111	inf_id_27	19	45	1201	6015	117,677
float_id_4	5132	154.9326	-3.17	move_id_201	12PA6B	LM2500+	600	28.9	10194	10489	13111	inf_id_33	15	60	1243	6776	115,413

Example Implementation: Down Select Combined Float-Move-Inf Functional Group Opt's

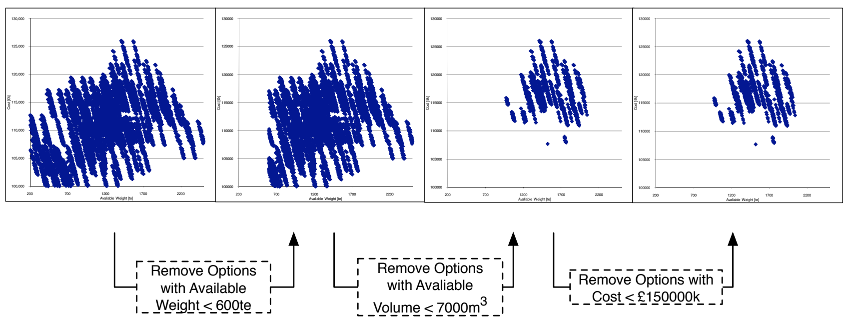
Overview of data flow in the example implementation



Effect of down select on number of remaining Options



Graphical representation of the effect of down select on number of remaining Options



Selection of solution data

	Inputs	From Geo	Sea-keeping		Inputs			Top speed	Range at speed given below [nm]				Inputs		Total Ship Characteristics		
	∇ [te]	L [m]	Sk rank		PM1	PM2	Fuel [te]		15 kts	20 kts	25 kts		Officers	Stores Endurance	∇-Mf+m+i [te]	V-Vf+m+i [m3]	Cf+m+i [£k]
float_id_32	5609	125.79	-4.16	move_id_222	12PA6B	LM6000	600	28.5	10129	10489	13111	inf_id_24	15	45	1916	9364	112,378
float_id_32	5609	125.79	-4.16	move_id_222	12PA6B	LM6000	600	28.5	10129	10489	13111	inf_id_25	15	45	1906	9233	112,883
float_id_32	5609	125.79	-4.16	move_id_222	12PA6B	LM6000	600	28.5	10129	10489	13111	inf_id_26	17	45	1885	8934	114,025
float_id_32	5609	125.79	-4.16	move_id_222	12PA6B	LM6000	600	28.5	10129	10489	13111	inf_id_27	19	45	1859	8579	115,378
float_id_32	5609	125.79	-4.16	move_id_222	12PA6B	LM6000	600	28.5	10129	10489	13111	inf_id_33	15	60	1902	9340	113,115
float_id_32	5609	125.79	-4.16	move_id_222	12PA6B	LM6000	600	28.5	10129	10489	13111	inf_id_34	15	60	1891	9208	113,661
float_id_32	5609	125.79	-4.16	move_id_222	12PA6B	LM6000	600	28.5	10129	10489	13111	inf_id_35	17	60	1868	8906	114,888
float_id_32	5609	125.79	-4.16	move_id_222	12PA6B	LM6000	600	28.5	10129	10489	13111	inf_id_36	19	60	1841	8548	116,342
float_id_32	5609	125.79	-4.16	move_id_223	16PA6B	LM6000	600	28.8	9616	7643	9554	inf_id_24	15	45	1907	9320	112,477
float_id_32	5609	125.79	-4.16	move_id_223	16PA6B	LM6000	600	28.8	9616	7643	9554	inf_id_25	15	45	1897	9189	112,982
float_id_32	5609	125.79	-4.16	move_id_223	16PA6B	LM6000	600	28.8	9616	7643	9554	inf_id_26	17	45	1876	8889	114,124
float_id_32	5609	125.79	-4.16	move_id_223	16PA6B	LM6000	600	28.8	9616	7643	9554	inf_id_27	19	45	1850	8535	115,477
float_id_32	5609	125.79	-4.16	move_id_223	16PA6B	LM6000	600	28.8	9616	7643	9554	inf_id_33	15	60	1893	9296	113,214
float_id_32	5609	125.79	-4.16	move_id_223	16PA6B	LM6000	600	28.8	9616	7643	9554	inf_id_34	15	60	1883	9164	113,760
float_id_32	5609	125.79	-4.16	move_id_223	16PA6B	LM6000	600	28.8	9616	7643	9554	inf_id_35	17	60	1860	8861	114,987
float_id_32	5609	125.79	-4.16	move_id_223	16PA6B	LM6000	600	28.8	9616	7643	9554	inf_id_36	19	60	1832	8503	116,441
float_id_32	5609	125.79	-4.16	move_id_224	20PA6B	LM6000	600	29.0	9192	5980	7475	inf_id_24	15	45	1898	9277	112,560
float_id_32	5609	125.79	-4.16	move_id_224	20PA6B	LM6000	600	29.0	9192	5980	7475	inf_id_25	15	45	1888	9145	113,065
float_id_32	5609	125.79	-4.16	move_id_224	20PA6B	LM6000	600	29.0	9192	5980	7475	inf_id_26	17	45	1867	8846	114,207
float_id_32	5609	125.79	-4.16	move_id_224	20PA6B	LM6000	600	29.0	9192	5980	7475	inf_id_27	19	45	1842	8491	115,560
float_id_32	5609	125.79	-4.16	move_id_224	20PA6B	LM6000	600	29.0	9192	5980	7475	inf_id_33	15	60	1884	9253	113,297

Appendix E

Comparative Designs

This appendix contains data on the two comparative designs used in the assessment of the exploratory implementation from Chapter 6:

- Figure E.1, on page 295, gives the key characteristics of the SDE 2007 design, from [Riaz et al. 2007];
- Figure E.2, on page 296, gives the key characteristics of the Cassard Class solution, from [Janes 2003].

Principle Characteristics		Payload Weapons Fit
Cost	£297.4 million	
Displacement (Deep/Light)	5360 / 4264 tonnes	8 x RBS15
LBP/LOA	134.1 m / 140.5 m	48 x Aster 30
Beam (extreme)	17.8 m	16 x TLAM (fit to receive)
Depth	12.0 m	MTLS
Draught (deep)	5.0 m	Sampson Multi Function Radar
Speed (Maximum)	28 knots	S1850 LREW radar
Endurance (Fuel)	13600 nm @ 14 knots	2 x Composite Mast
Endurance (Stores)	40 days	1 x 155mm Gun
In Service Date	2015, Batches of 3	2 x Phalanx CIWS
Design Hull Life	30 years	2 x 30mm Gun
Complement	155	1 x Lynx, Single Spot Flightdeck (Fit to receive Merlin)
Accommodation	180	Hull Mounted Active/Passive Sonar
Propulsors		
2 x pods		2 x Fixed Pitch Propellers
Integrated Full Electric Propulsion		Integrated Platform Management System
1 x Rolls Royce WR21 GTA (25 MW)		4160V, 60Hz Propulsion Busbar, 650V DC Ship's Service Busbar
3 x Wartsila 12V26 DG (3.745 MW)		Wartsila Auxpac 975W6L20 Harbour/Emergency DG (975 kW)
2 x High Temperature Superconducting Motors – Podded (15 MW)		2 x PWM Converters

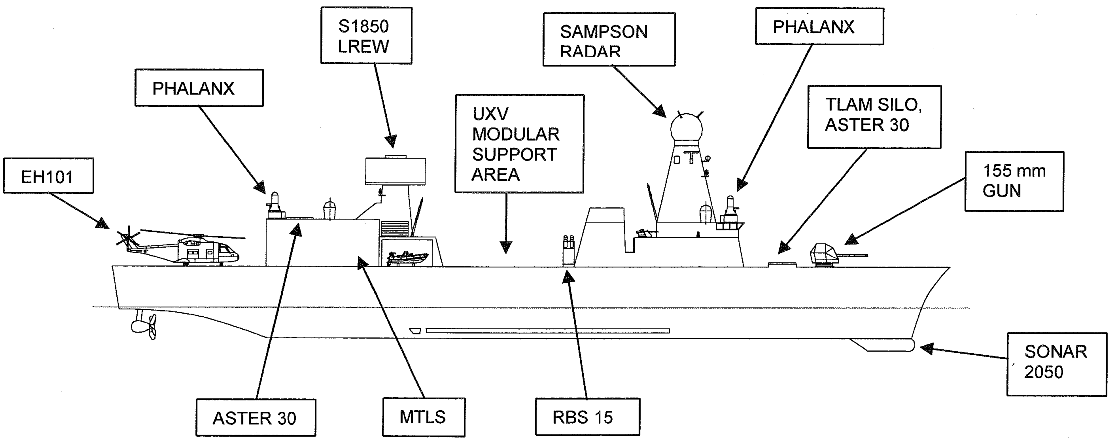


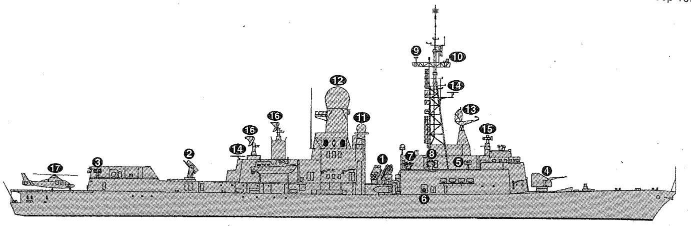
Figure E.1: Student Design from the MSc Ship Design Exercise 2007, from [Riaz et al. 2007]

2 CASSARD CLASS (TYPE F 70 (A/A)) (DDGHM)

Name	*No*	*Builders*	*Laid down*	*Launched*	*Commissioned*
CASSARD	D 614	Lorient Naval Dockyard	3 Sep 1982	6 Feb 1985	28 July 1988
JEAN BART	D 615	Lorient Naval Dockyard	12 Mar 1986	19 Mar 1988	21 Sep 1991

Displacement, tons: 4,230 standard; 5,000 full load
Dimensions, feet (metres): 455.9 × 45.9 × 21.3 (sonar) *(139 × 14 × 6.5)*
Main machinery: 4 SEMT-Pielstick 18 PA6 V 280 BTC diesels; 43,200 hp(m) *(31.75 MW)* sustained; 2 shafts
Speed, knots: 29.5. **Range, miles:** 8,000 at 17 kt.
Complement: 244 (22 officers) accommodation for 251

Missiles: SSM: 8 Aerospatiale MM 40 Exocet ❶; inertial cruise; active radar homing to 70 km *(40 n miles)* at 0.9 Mach; warhead 165 kg; sea-skimmer.
SAM: 40 GDC Pomona Standard SM-1MR; Mk 13 Mod 5 launcher ❷; semi-active radar homing to 46 km *(25 n miles)* at 2 Mach; height envelope 45-18,288 m *(150-60,000 ft)*. Launchers taken from T 47 (DDG) ships.
2 Matra Sadral PDMS sextuple launchers ❸; 39 Mistral; IR homing to 4 km *(2.2 n miles)*; warhead 3 kg; anti-sea-skimmer; able to engage targets down to 10 ft above sea level.
Guns: 1 DCN/Creusot-Loire 3.9 in *(100 mm)*/55 Mod 68 CADAM automatic ❹; 80 rds/min to 17 km *(9 n miles)* anti-surface; 8 km *(4.4 n miles)* anti-aircraft; weight of shell 13.5 kg.
2 Oerlikon 20 mm ❺; 720 rds/min to 10 km *(5.5 n miles)*.
4—12.7 mm MGs.
Torpedoes: 2 fixed launchers model KD 59E ❻. 10 ECAN L5 Mod 4; anti-submarine; active/passive homing to 9.5 km *(5.1 n miles)* at 35 kt; warhead 150 kg; depth to 550 m *(1,800 ft)*.
Countermeasures: Decoys: 2 CSEE AMBL 1B Dagaie ❼ and 2 AMBL 2A Sagaie 10-barrelled trainable launchers ❽; fires a combination of chaff and IR flares. Dassault LAD offboard decoys. Nixie; towed torpedo decoy.
ESM: Thomson-CSF ARBR 17B ❾; radar warning. DIBV 1A Vampir ❿; IR detector (integrated with search radar for active/passive tracking in all weathers). Saigon radio intercept at masthead.
ECM: Thomson-CSF ARBB 33; jammer; H-, I- and J-bands.



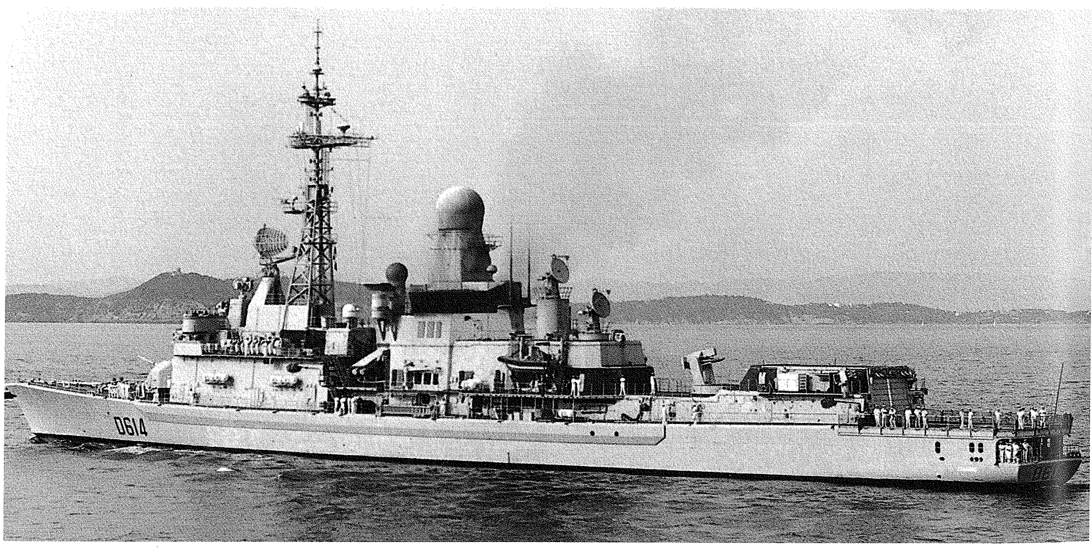
CASSARD *(Scale 1 : 1,200), Ian Sturton*

Combat data systems: SENIT 68; Links 11, 14 and 16. Syracuse 2 SATCOM ⓫. OPSMER command support system.
Weapons control: DCN CTMS optronic/radar system with DIBC 1A Piranha II IR/TV tracker; CSEE Najir optronic secondary director.
Radars: Air search: Thomson-CSF DRBJ 11B ⓬; 3D; E/F-band; range 366 km *(200 n miles)*.
Air/surface search: Thomson-CSF DRBV 26C ⓭; D-band.
Navigation: 2 Racal DRBN 34A; I-band (1 for close-range helicopter control ⓮).
Fire control: Thomson-CSF DRBC 33A ⓯; I-band (for guns).
2 Raytheon SPG-51C ⓰; G/I-band (for missiles).
Sonars: Thomson Sintra DUBA 25A (D 614) or DUBV 24C (D 615); hull-mounted; active search and attack; medium frequency.

Helicopters: 1 AS 565SA Panther ⓱.

Programmes: The building programme was considerably slowed down by finance problems and doubts about the increasingly obsolescent Standard SM 1 missile system. Service lives: First, 2013; second, 2015. Re-rated F 70 (ex-C 70) on 6 June 1988, officially 'frégates anti-aériennes (FAA)'.
Modernisation: DRBJ 15 radar initially fitted in *Cassard* but this was replaced in 1992 by DRBJ 11. Panther has replaced Lynx helicopter. *Cassard* refitted 2000-2001. Upgrade included hull strengthening, fitting of new propellers and SENIT 68 combat direction system (SENIT 6 core augmented by SENIT 8 data-link processing component (for Link 16 and data forwarding). *Jean Bart* being similarly refitted 2002-03. Plans to fit ASTER 30 have been abandoned. Both ships to be replaced by second batch of 'Horizon' class from 2012.
Structure: Samahe 210 helicopter handling system.
Operational: Helicopter used for third party targeting for the SSM. Both ships are based at Toulon.

UPDATED



CASSARD (post refit) *7/2002*, B Prézelin / 0528954*

Figure E.2: Characteristics of the Cassard Class ships, from [Janes 2003]

Appendix F

The Improved Implementation

F.1 Description of the Improved Implementation

Object-oriented and array based programming approaches have been described in Section 4.4.1. The potential advantages of databases, compared to other data storage structures, were discussed in Section 4.4.2. From the various strengths, these two approaches have been explored to improve the initial implementation. Databases provide an alternative approach to data storage for design options. Adopting a database storage system enables the down selection process to make use of the database's rapid search and query capabilities to search a large number of options stored in a computers relatively slow storage mediums (i.e. hard-disk drive). Options returned to the implementation from the database storage can then be realised as instances of objects[1] within the computers faster but limited direct memory (i.e. Random Access Memory). These instances can then be down selected and combined in the same manner as in the exploratory example in Chapter 6. In that implementation, data was replicated numerous times in the code. If instead pointers, referring to the original objects containing the data, are used then they no longer need to be duplicated, avoiding a computationally demanding task that is both processing and memory intensive. Furthermore, removing unacceptable options will immediately release the space in the computers direct memory that was occupied by the object representing the option that has been rejected. This approach simplifies data management within the implementation and allows more efficient use of the computer's memory. An object based implementation also enables radically differing solutions to be more easily represented, stored and retrieved an encapsulation can allow differing type of options be be represented by object that respond in different ways. This allows the library to hold options representing a range of styles. Different types of options are likely to require different methods to calculate certain performance parameters or other ship characteristics. Adopting an array based programming approach in concert with an object-oriented approach allows a large

[1]In object-oriented programming approaches there is an important distinction between an object and an instance of an object. An object is actually a definition, or a template, for instances of that object that form part of a program. An instance of an object is an actual thing, represented in the computers memory, that is manipulated when a program is executed. However, the collective term 'object' is commonly applied to describe an object in both it's un-instanced and instance form.

number of objects to be acted upon with a single command, reducing the effort required to develop the implementation and simplifying its structure. By developing a more flexible implementation which employs an object-oriented, array based programming approach, that is backed by a database driven storage system, significant increases of speed and improved memory efficiency are possible. This can result in a system which is more useful to a designer than the initial realisation presented in Chapter 6.

The improved implementation has been built from several different objects that act together to create a data model able to perform the key tasks underlying the approach proposed in Chapter 5. The seven primary objects that form the improved implementation are[2]:

- Items
- Characteristics
- Values
- Conditions
- Functions
- Styles
- Characteristic Types

The first four objects in this list represent ship design options (and sub-options) and their properties. The last three objects in the list provide a framework and structure allowing the designer to intelligently search for solutions, when using the Library Based approach. Connections between the different objects are maintained via a number of different relationships. Other researchers have described similar structure intended to store information on ship designs (see Chapter 7 of [Erikstad 1996]), however, using the objects listed above gives specific advantages for a tool that utilises the proposed library based approach and also employs a database system for storage.

Section F.1.1 describes the objects and relationships as defined in this specific implementation focusing on the objects stored in the library. Section F.1.3 describes the methods the improved implementation uses to process the objects from the library. Section F.1.6 provides a summary of the technical details of the improved implementation.

F.1.1 Principal Objects Stored in the Library

Each option (or sub-option) in the Library is defined using a single Item object linked to several Characteristic objects that describe the options characteristics and performance

[2] In this chapter the objects within the improved implementation are denoted by small caps.

(e.g. 'length', 'weight', 'power', etc). ITEMS are structured via FUNCTIONS & STYLES. Each ITEM is defined as belonging to a FUNCTION, which specifies its functional group (i.e. 'Float', 'Move', 'Infrastructure' and 'Whole Ship'). ITEMS can also be assigned a number of STYLES; these provide a means of differentiating between different styles of solutions that occur in a single functional group (such as 'Monohull' and 'Trimaran', as two alternative styles an option belonging to the Float functional group could be allocated by the designer).

Each item can be allocated a number of CONDITION objects that define the different modes or states in which it may operate (i.e. a hullform may operate at several different speeds, each with a resultant hull resistance). CHARACTERISTICS are organised using a CHARACTERISTIC TYPE (such as Length, Weight and Power Supplied) which provides a common way of identifying CHARACTERISTICS. Each CHARACTERISTIC can also be related to a number of VALUE objects. VALUE objects correspond to the value the CHARACTERISTIC exhibits in a particular condition, defined by a CONDITION object (such as the values for power supplied and fuel consumed by the machinery in different operating states).

A number of the objects within the library contain attributes that store text or numerical data specific to the particular object. In the current implementation instances of the ITEM, CHARACTERISTIC TYPE, FUNCTION, STYLE, and VALUE objects all contain attributed that are used to describe. The ITEM and CHARACTERISTIC TYPE objects contain a text field describing the name of the object (e.g. "Hull-001"). Similarly, each FUNCTION and STYLE object contains a text field with the objects name. The numerical data describing the option's characteristics and performance can be recorded in two ways, either as a single numerical value stored as an attribute within each CHARACTERISTIC (should the value be constant across all operating conditions; i.e. ship length) or a number of relationships can be created to several VALUE objects, each of which has the defined CHARACTERISTIC'S value in a particular CONDITION (should the value vary between operating conditions; i.e. the required propulsive power corresponding to a particular operating speed). Both types of value are currently limited to a single attribute representing a floating point number. While this has not limited the development and exploration of this implementation, the ability to represent other types of values would enhance the flexibility of future implementations.

The key objects making up the library in the improved implementation are illustrated in Figure F.1. The diagram shows each object's attributes (the variables stored within the object) and the relationships the object has to other objects in the Library. Each object is represented as a rectangle split into three sections: the top section contains the object's type (i.e. "ITEMS"); the middle section contains the attributes the object can return (such as the name of an item object, i.e. "Item-1"); the bottom section defines the relationships the object has with other objects (i.e. relationships of an ITEM object to related CHARACTERISTICS, FUNCTION, STYLE, and CONDITION objects). Each relationship is

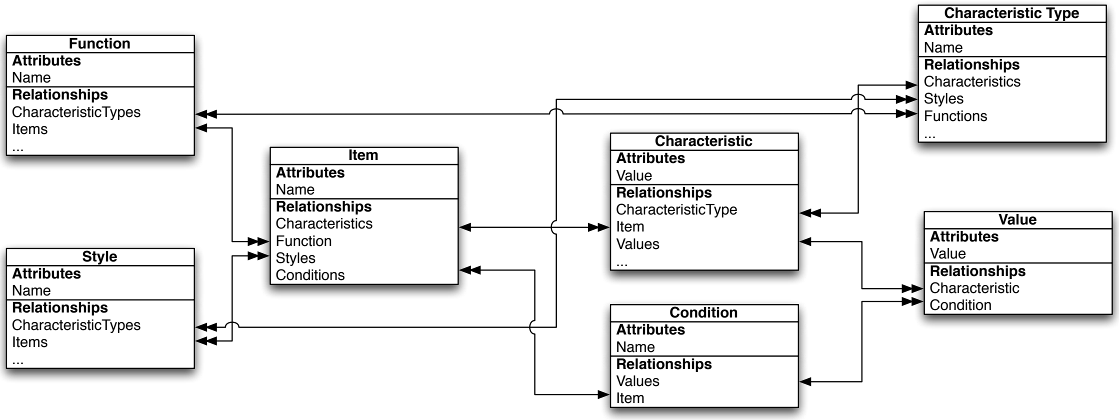


Figure F.1: Key Objects within the Library

also illustrated in Figure F.1 by an arrow. A single arrow denotes a to–one relationship while a double arrow denotes a to–many relationship. For example, an Item object may contain relationships linking it to several Characteristic objects (i.e. connected by a to–many relationship) while each Characteristic object can only be related to a single Item object (i.e. only connected by a to–one relationship). This description of the objects with relationships allows the objects within the Library to be mapped to a relational database structure, which allows storage and rapid retrieval given a set of constraints.

Figure F.2 presents a simplified example of how a library containing a number of options is organised. It should be noted that the data structure describing each Item object is related to its own Characteristic, Condition and Value objects but shares common Characteristic Type, Function and Style objects[3].

[3]For example, Figure F.2 shows two Item objects ('Hull-001' and 'Hull-002') and their associated sub-objects. The item object and sub-object have been enclosed within a dashed line in the figure and label ed 'Float Option 1' and 'Float Option 1' (for 'Hull-001' and 'Hull-002' respectively). Each Item has two Characteristic objects, one linked to a Characteristic Type defined as 'Speed' and the other to a Characteristic Type defined as 'Resistance'. The Item also has three of Condition objects defined: 'high speed'; 'medium speed'; and 'low speed'. The actual attributes of the Item object are recorded in a number of Value objects. In the case of 'Hull-001' six values exist, three describing the changing resistance of the hullform and three the speed at which these resistance were measured. Each value is assigned to a Characteristic object (e.g. the '1000', '1800', and '5000' Value objects are linked to the Characteristic object that is in turn linked to the Characteristic Type defined as 'Resistance', similarly the '10', '20', and '30' Value objects are linked a second Characteristic object to a Characteristic Type defined as 'Speed'). The Condition objects are used to link Value objects that represent different characteristics that occur in the same state (e.g. the Condition object for 'low speed' is linked to the values for '10' (for speed) and '1000' (for resistance)). This provides a flexible structure for adding more substantial quantities of information. Furthermore, each option can be allocated differing number of Characteristics depending upon the values that are of interest (e.g allowing differing number of characteristics for monohull and trimaran hullform options stored in the library). Finally, a variable number of Condition objects per option allows the options to represent the available information as opposed to forcing or constraining the available information to fit a certain predetermined database structure.

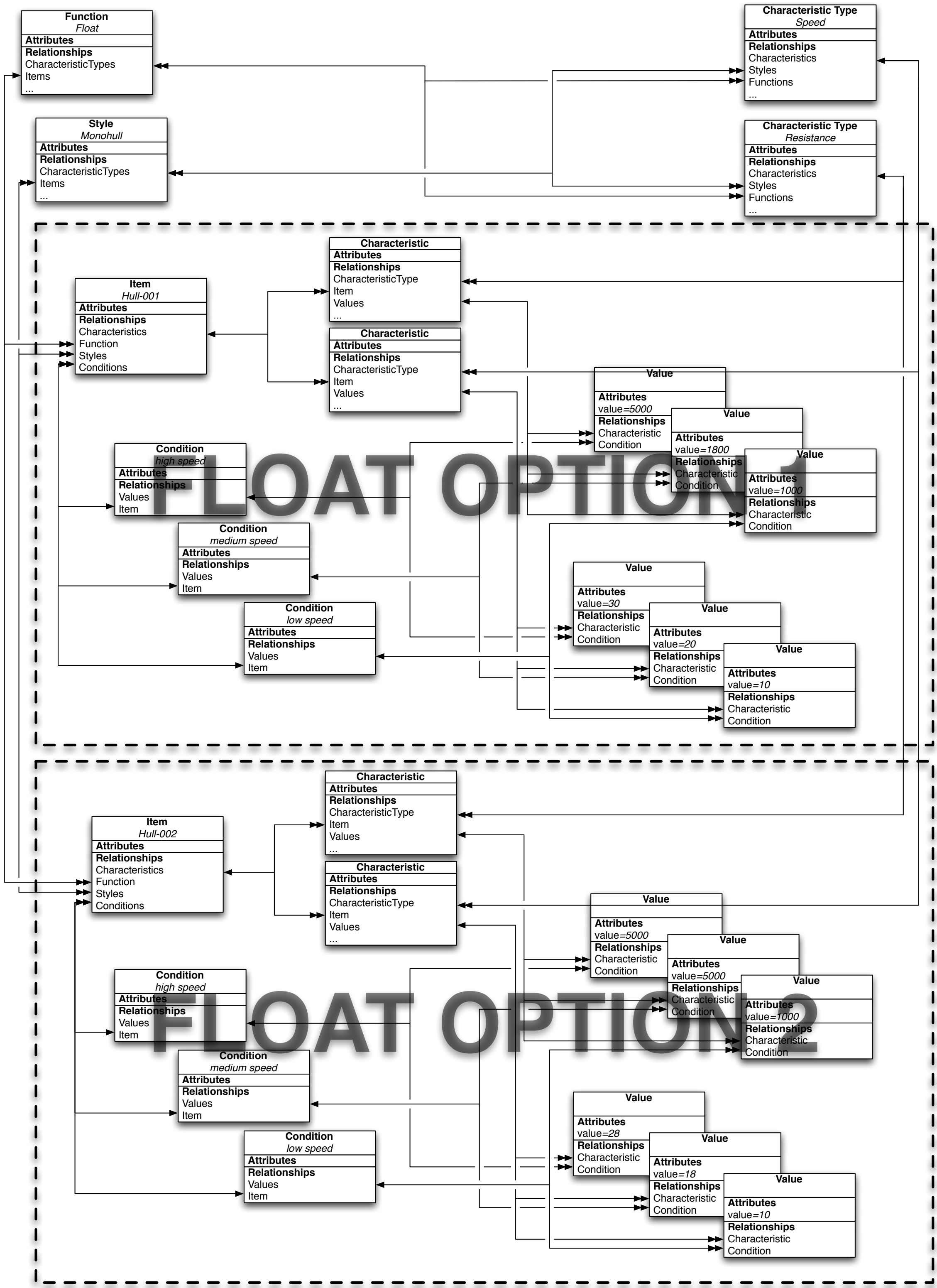


Figure F.2: Example of Two Options within a Simple Library

Separation of Functions and Styles

As described earlier each ITEM within the improved implementation must be assigned a relationship to a FUNCTION object (i.e. Float, Move, etc.) and a number of STYLE objects (i.e. different hullform types: monohull, SWATH, Trimaran, etc.). FUNCTION objects represent the different functional elements of an option, all ITEMS objects in the library belong to a specific part of the functional decomposition applied to the complete system (i.e. ship) represented in the library. Applying a specific functional decomposition requires the definition of a set of characteristics that act across any inter-functional interface; this allows the common characteristics of all sub-objects of a given function to be determined. Therefore, each FUNCTION object can logically be assigned a number of related CHARACTERISTIC TYPE objects that are compulsory. Table F.1 shows an example of a functional hierarchy from within the design (in common with the Andrews and Dicks [1997] approach).

Table F.1: Example Function Hierarchy

Functions	Characteristics Required for Function
Ship	Unallocated Weight; Unallocated Volume; Cost.
→Float	Overall length; Overall beam; Maximum draught; Resistance at given speed[a].
→Sustension	Displacement.
→Subdivision	Bulkhead positions.
→Strength	Maximum bending moment.
→Move	Thrust for given operating duration[a].
→Propulsion	Thrust at given fuel consumption[a].
→Prime Movers	Fuel consumption and power output at given RPM[a].
→Transmission	Power input and power output at given RPM[a].
→Propulsors	Power input and Thrust at given RPM[a].
→Energy storage	Fuel capacity.

[a]These characteristics normally consist of a set of values for different conditions.

Style can be employed as an additional mechanism for distinguishing between options with identical functional roles but which are configured in radically different ways. Section 2.4.1 provides several different examples of areas styles (i.e. Sustension, Arrangement and Topology) which functionally common hullforms could adopt. As an option can possess multiple styles (i.e. trimaran, double hulled, steel) each ITEM object may be assigned a relationship to several STYLE objects. These STYLE objects are associated with a number of other CHARACTERISTIC TYPES. Adding a STYLE object to an ITEM object expands the Characteristic Types that any new Characteristics, added to the Item, can adopt. Table F.2 shows an example of a hierarchy of styles[4]. In this implementation Styles also inherit the characteristics of their parent Styles in the hierarchy (i.e. the Catamaran Style has the following typical characteristics: Overall length; Overall beam; Displacement; Resistance–Speed; Demi-hull separation; Box clearance; Demi-hull waterline beam; and Demi-hull waterline length).

Table F.2: Example Style Hierarchy

Styles	Characteristics Required for Style
Base Hullform Style	Overall length; Overall beam.
→Hydrostatic Sustension	Displacement; Resistance–Speed[a].
→Monohull	Waterline beam; Waterline length.
→Twin-hull	Demi-hull separation; Box clearance.
→Catamaran	Demi-hull waterline beam; Demi-hull waterline length.
→SWATH	Bulb radius; Strut length; Strut beam.
→Tri-hull	Side-hull separation.
→Trimaran	Main hull waterline beam; Main hull waterline length; Side hull waterline beam; Side hull waterline length.
→Triswath	Bulb radius; Bulb depth; Strut length; Strut beam; Main hull waterline beam; Main hull waterline length.
→Hydrodynamic Sustension	Displacement–Speed[a]; Dynamic lift–Speed[a]; Draught–Speed[a]; Resistance–Speed[a].
→Hydrofoil	Foil cord; Foil span.

[a]These characteristics normally consist of a set of values for different conditions.

The possible characteristics of each Item object are defined via the union of the characteristic type objects related to the Items object's Function and Style objects. Considering the a catamaran hullform, once this has been assigned a 'Float' function and a style of 'Catamaran', then the complete set of characteristics can be built up. The style of 'Catamaran' inherits the styles of 'Twin-hull', 'Hydrostatic Sustension' and 'Base Hullform Style'. By amalgamating the characteristics of these different styles a comprehensive set of characteristics for the catamaran hullform can be obtained. This gives the following list of (basic[5]) characteristics: Overall length; Overall beam; Maximum draught; Resistance at

[4]It should be noted that the styles shown in Table F.2 are limited to hullform styles. However, as discussed in Sections 2.3.1 and 2.4.1, the definition of style provided by Andrews [1984] is a far broader, encompassing issues that appear across the whole ship.

[5]Clearly any ship design has a very extensive set of characteristics by the end of full design but given this research focuses on concept design only the 'basic' set of characteristics, for a particular ship style, is

given Speeds; Demi-hull waterline beam; Demi-hull waterline length; Demi-hull separation; Box clearance; Displacement; Overall length; and Overall beam.

Item Templates Objects

It may be inconvenient to require a user to specify a complete set of CHARACTERISTIC objects for each item added to the library. In some cases the information may not be available or the resources required to add many attributes to these new objects may be disproportionate. In these cases ITEM TEMPLATE objects can be used to provide a blueprint for any missing item attributes. While not one of the principal objects introduced in Section F.1, ITEM TEMPLATE objects are similar to ITEM objects. Each ITEM TEMPLATE object contains the definition of a number of CHARACTERISTICS together with either a default numerical value or an appropriate performance prediction method with which to calculate the numerical value (see Section F.1.2). This implementation of the library based tool only allows a single ITEM TEMPLATE to be defined for each FUNCTION object. While sufficient for the demonstration presented in this chapter, a more powerful implementation could allow ITEM TEMPLATE objects to be defined for each STYLE object. This would allow the performance prediction methods used by any ITEM object to be inferred from the object's STYLES, thus allowing the most suitable method to be applied.

Items Objects and Sub-Items

In the proposed Library Based approach a frequently occurring activity is the combination of a number of input sub-options into a new combined option. The exploratory implementation presented in Chapter 6 utilised a process where the data for input sub-option's was duplicated and then combined to form a set of data for the new combined option. Then all additional required characteristics were calculated for each combined option. This was identified as a disadvantage of the exploratory implementation. The improved implementation presented in this chapter utilises a different approach offering significant performance advantages over the exploratory implementation.

In the improved implementation all ITEM objects have been given the ability to act as both a combined option and a sub-option. Each ITEM object can contain an array of references to a number of other ITEM objects, which are termed SUB-ITEMS. An unlimited number of SUB-ITEMS can be defined, allowing the library to be developed to a depth determined by the designer. For example, a designer could choose to further decompose a Move sub-option, as shown in Table F.1.

Combining a number of ITEM objects to form a new combined option consists of two steps: first, a new ITEM object is created; then references to the ITEM objects that represent

requires for the Library approach proposed. Although the Library Based approach does not limit the set of characteristics the designer can add to the library.

the sub-options are set in the new Item object. When initially created this new Item object has no related Characteristic objects. Should the user request an attribute from this new Item, the mechanism detailed in the following sub-section is applied.

Attributes for an Item

Section 4.4.1 discussed how object-oriented programming methods are used to perform operations on an object or obtain information on the values of an object's variables. This section discusses the steps that occur in the improved implementation when an Item object is requested to provide the numerical value for a particular Characteristic Type[6] and hence a requested attribute for an option. This begins a chain of steps in the implementation that provide a numerical value. The steps taken are:

1. Initially each of the Item object's Characteristic objects are checked to see whether their Characteristic Type matches the requested Characteristic Type. If a match is found then the numerical value stored within the matching Characteristic object is provided;

2. Next the appropriate Item Template object's Characteristic objects are checked to see whether their Characteristic Type matches the requested Characteristic Type. If a match is found then a copy of the Item Template object's Characteristic is created for the Item object. The numerical value stored within the this newly created Characteristic is provided;

3. Finally the Item object's Sub-Items (representing any sub-options previously combined to create this option) are checked to see whether they return a numerical value for the requested Characteristic Type. Any numerical values returned are totalled and this total is provided.

These three steps are illustrated in Figure F.3 to F.5. Figure F.3 provides an example of how a numerical attribute for an Item, representing a Move functional sub-option, would be retrieved for the Characteristic Type of 'Maximum power'. First the Item object's

[6] The term request is used, as the actual action performed is opaque to the user as all object encapsulate the actions they perform, shielding the user from their precise internal implementation. Consider the following example code that initiates the process in the program to find the numerical value for an Item object given a particular Characteristic Type object:

```
aNumber = [anItemObject valueForCharacteristicType:aCharacteristicsTypeObject];
```

This code is composed of a message (enclosed between the square brackets) and an output variable ('`aNumber`') which records the result returned by the message. The message is composed of two parts: a target object to which the message is directed (in this case an Item object, '`anItemObject`') and a message ('`valueForCharacteristicType:`') with a parameter (in this case a Characteristic Type object, '`aCharacteristicsTypeObject`'). The message only returns the numerical value; the process that is object undertook to obtain this value is hidden from the user.

Characteristics are checked in turn to find if their Characteristic Type matches the requested Characteristic Type (i.e. ‘Maximum power’). In this case, the Item object has a single Characteristic object that matches the requested Characteristic Type (i.e. ‘Maximum power’). The single Value object associated with this Characteristic object is accessed, and the numerical value stored within it provide (e.g. ‘5000’).

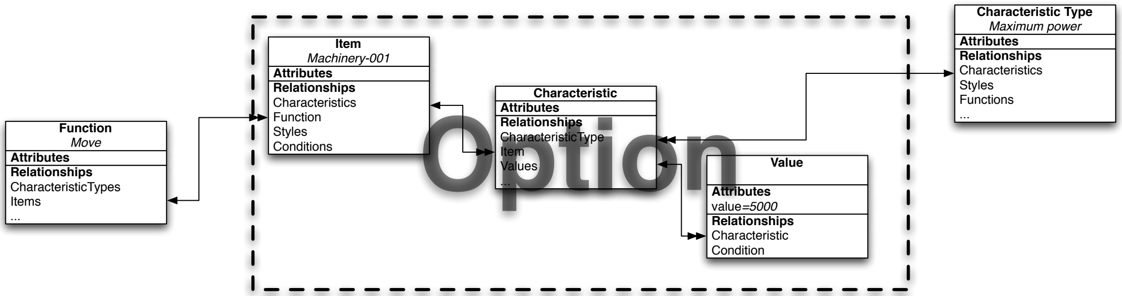
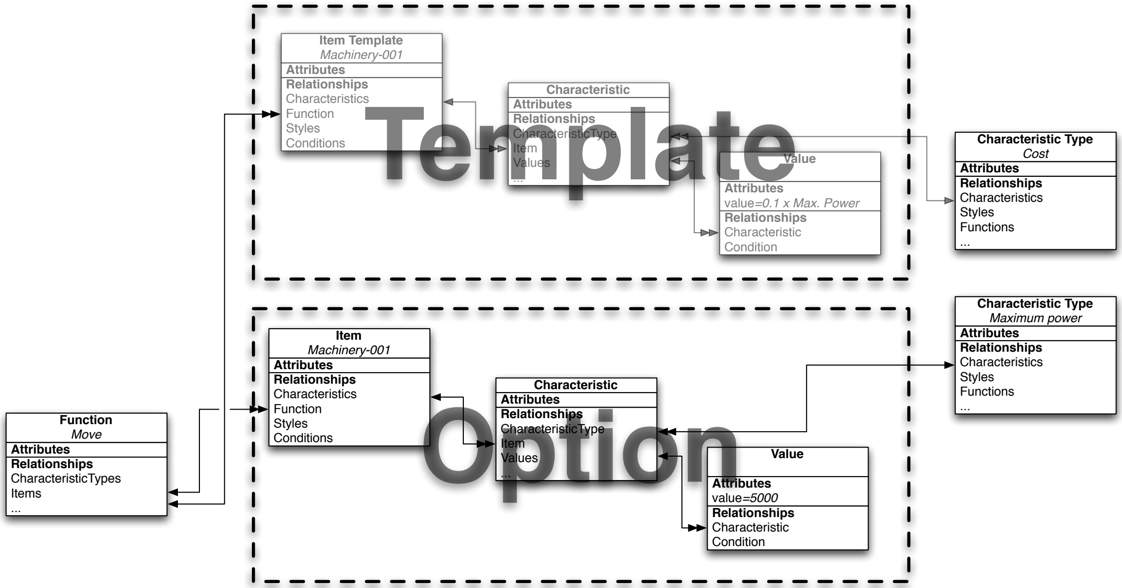


Figure F.3: Numerical Value from Item object’s Characteristics

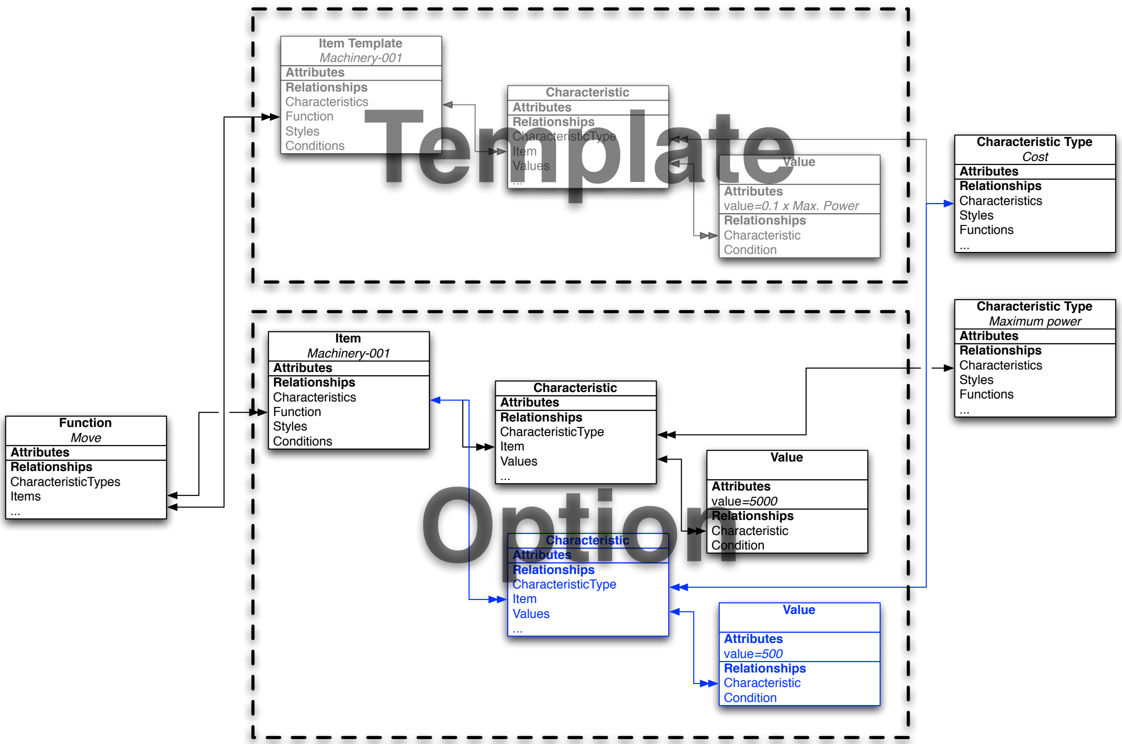
The next example, illustrated in Figure F.4, considers a request for the numerical attribute for the ‘Cost’ Characteristic Type of an Item representing a Move sub-option. First, the Item object’s Characteristics are checked in turn, however in the case shown in Figure F.4a none of the Item object’s Characteristics match the requested Characteristic Type. Therefore, the Item Template is retrieved and its Characteristics inspected. A Characteristic with a matching Characteristic Type is found within the Item Template and this Characteristic object is used as a template to create a new Characteristic in the Item (as shown in Figure F.4b, the newly created objects are coloured blue). In the example shown in Figure F.4b the Value of the Characteristic in the Item Template contains a formula for determining the required cost, which is based upon the installed power (i.e. ‘value $= 0.1 \times$ Maximum power’). This is used with the Item’s other Characteristic objects to determine the correct numerical value (i.e. ‘500’), which is then provided.

Finally, Figure F.5 shows an example of the steps that occur when neither the Item nor the Item Template responds to the requested Characteristic Type. In this case, neither the Item nor Item Template possesses a Characteristic that matches the ‘Weight’ Characteristic Type. The implementation then sequentially checks the Item object’s Sub-Items for a response to the Characteristic Type. The numerical values from any responses are then totalled, and this total is then provided. In the example shown in Figure F.5 a value of ‘400’ would be provided.

For each of these cases, the mechanism used to provide numerical attributes is identical. If the Value already exists then a numerical value is simply provided. If the value is undefined then a performance prediction method has to be applied to quickly determine an approximate value, as detailed in Section F.1.2.



(a) Initial Objects Representing the Item and Item Template



(b) Objects After a New Characteristic, based upon the Item Template, is added to the Item

Figure F.4: Numerical Value from Item object's Characteristics using an Item Template object

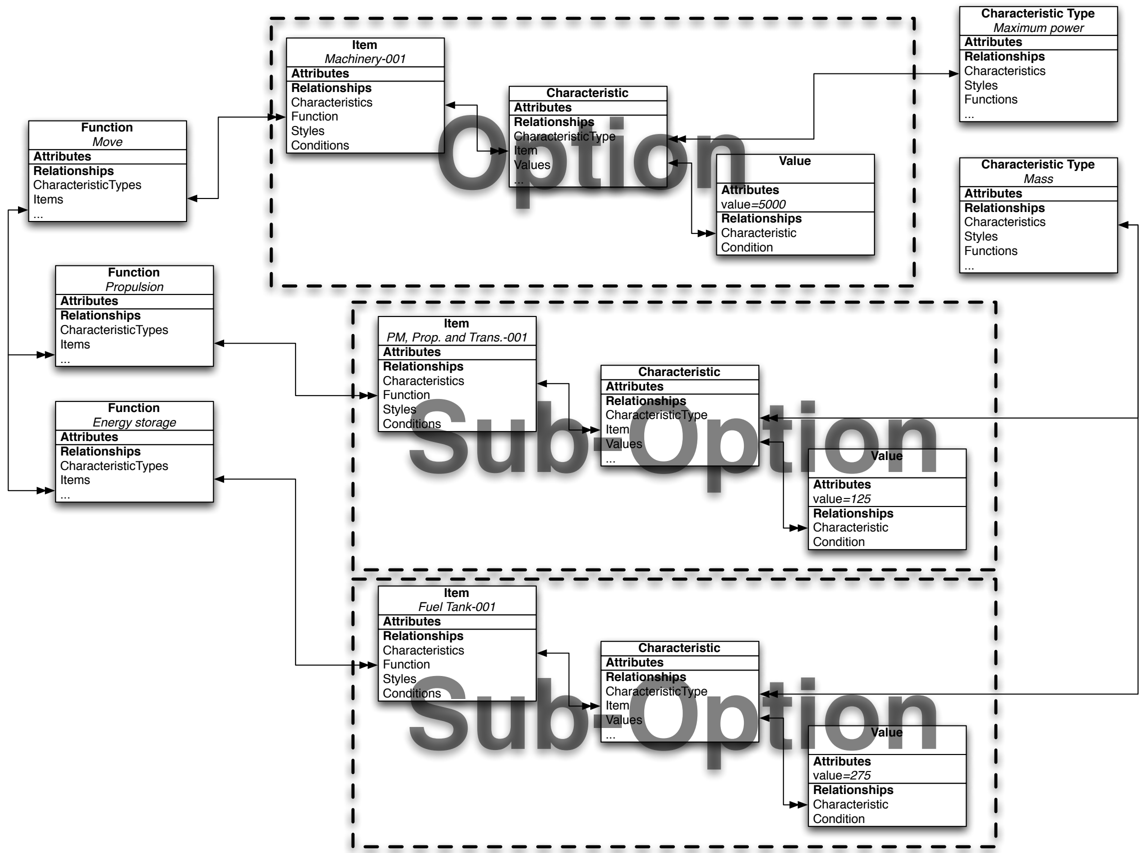


Figure F.5: Numerical Value from Item object's Sub-Items

F.1.2 Performance Prediction in the Improved Implementation

It is not feasible to pre-calculate and store all attributes that may be of interest to the designer. However, some attributes can be inferred or estimated from the value of the option's other attributes. Alternatively an appropriate performance prediction method can be used to rapidly calculate these values. As discussed in Section 5.3.2, a wide variety of different performance prediction methods are available, however those included in the current implementation have been limited to those which are quick to run and can be updated easily (akin to current preliminary ship design 'rules of thumb'). The performance prediction methods are setup and linked to item template objects before the tool is used to examine options within the library. All requests for a numerical value corresponding to a particular Characteristic Type follow an analogous pattern described in the final part of the preceding sub-section.

The example summarised in Figure F.4 showed how as Item Template could employ a simple formula as a performance prediction method to provide an approximate value for a missing attribute of an Item object. The advantage in the use of a flexible range of performance prediction methods becomes apparent when the wider design library is considered. For example, in the case of a set of options being down selected, using a cost requirement, then each object's cost attribute must be retrieved. If the Item objects that represent these options already have a cost attribute stored within the library then this can simply be provided. For Item objects without a pre-calculated and stored cost attribute, the appropriate Item Template will be used to access a suitable performance prediction method. That method will then be used to estimate the Item object's cost, based on the Item's other attributes. Costing methods based upon the weight of different elements of the design are readily available and could be easily applied. Other costing methods also exist: Sub-section 3.2.5 highlighted research that has applied artificial neural networks to obtain estimates of ship features, including cost, from limited inputs [Ray 1998]. A recurring problem with many artificial neural network based performance prediction methods is providing a suitable set of training data (as discussed in Section 3.2.5). However, a library based approach, with a growing library of various design options available, provides a readily accessible source of training data for a artificial neural networks (or another unsupervised learning methods). Thus, a performance prediction method employing an artificial neural network could be used to determine missing attributes through accessing other data from the library.

A similar approach could be adopted in other areas, such as resistance prediction. Data defining a Float option's resistance for a range of speeds (e.g. 10, 20 and 30 knots) could be pre-calculated using an appropriate resistance prediction tool[7]. Using this data the resistance at intermediate speeds could be determined by a performance prediction method (such as an interpolation approach, see [Lourakis 2008]). Alternatively, if there is no suitable performance data, the resistance of new solution could be assessed by using an artificial neural network trained using data from the other options within the library.

Although not a feature in the current implementation, applicable performance prediction methods could be determined from the Item object's styles, allowing the most appropriate methods to be used for each Item. For example, a performance prediction method used to estimate the stability characteristics of a monohull Float option could be different from that applied to multi-hull Float options. As all item objects within the library are related to specific Style objects, this would be simple to implement.

F.1.3 Actions within the Improved Implementation

The process of searching the library for appropriate sub-options and combining these to form new options, which are then presented to the designer, is performed by a number of actions. Actions are split into two types: Fetch actions that retrieve Item objects from the library and Combine actions that generate new options by combining sub-options belonging

[7] In the case of a multihull vessel this may be a computationally intensive tool based upon thin ship theory or boundary element methods [Bertram 2000]. However, as these calculation would take place before the designer uses the library, it would not cause significant delays in operating the library based approach.

to a number of input actions. These two types can be combined into a hierarchical tree of actions with Combine actions as 'branches' and Fetch actions as 'leaves', as shown in Figure F.6.

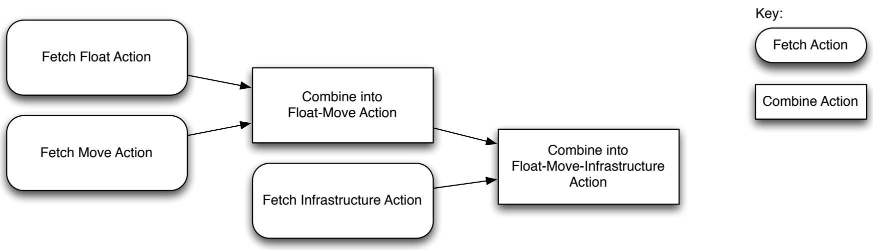


Figure F.6: Example Hierarchical Tree of Fetch and Combine Actions for the Improved Implementation of the Library Method

Both types of Actions allow requirements and constraints to be used to filter the options. Specifically the option's characteristics are checked to ensure that a characteristic exists that satisfies all applicable constraints (e.g. using a minimum length constraint to examine all Float options, removing those Items with a Characteristic object whose Characteristic Type matches 'length' and whose value fails to satisfy the constraint). Constraints are divided into two types: Simple constraints and comparison constraints. Simple constraints allow numerical constraint to be input by the user (e.g. length < 160m). Comparison constraints enable the characteristics of two sub-options to be compared (e.g. required power < available power). Options unable to satisfy these constraints are removed from consideration.

Fetch actions retrieve Items from the library. When fetching the Items the constraints are used to limit the retrieved items by removing those Items which fail to meet the constraints. However, in some cases a performance prediction method must be applied before a constraint can be checked, therefore the item objects which are provisionally retrieved must be fully checked against all constraints after being retrieved from the library. After the checks, the Fetch actions provide a set of item objects that satisfy the constraints.

Combine actions take as an input two sets of item objects from the Combine action's input actions, these sets are termed Input items. The Combine action generates all possible combinations of Input items from the two sets, identifying and discarding those that fail to satisfy the given constraints. For each combination of Input items, the Combine action encapsulates the following four steps:

1. Inspect Input items for incompatibilities with constraints. If incompatibilities are found this combination is discarded[8];

[8]Note that at this stage not all constraints may be able to be assessed. Missing characteristics cannot be assessed using a performance prediction method until a new Item representing the Combine options is created. If a constraint cannot be assessed is ignored until step 4.

2. Created a new Item;

3. Add Sub-Items, to the new Item, matching the current combination of Input items;

4. Inspect new Item for incompatibilities with constraints[9].

The Combine action returns a set of new Item objects that satisfy the constraints. These new objects contain pointers to the Item objects that were the Input items and they also contain new Characteristic objects for any attributes that have been evaluated as the action has been performed.

F.1.4 Strategies for Down Selections and Performance Prediction

The example above demonstrates how the current implementation of the Combine action can be used to assess options by sequentially examining a combination of Input items. As the Input items of the Combine action are actually two or more sets of options then more efficient strategies can be employed to examine potential combined options. Three possible strategies are:

A. Combine sub-options, then calculate Combined option's characteristics removing unacceptable Combined options;

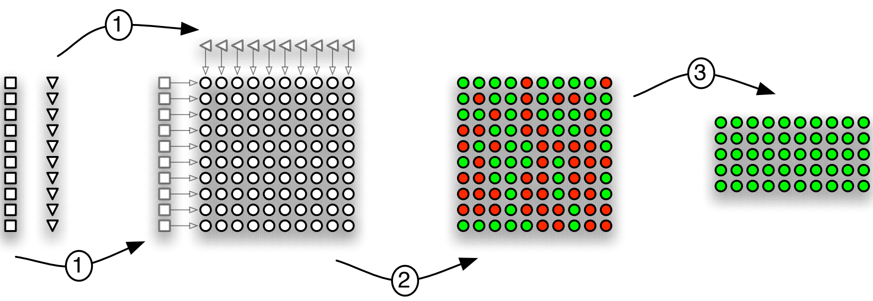
B. Calculate sub-option's characteristics, then compare sub-option's characteristics combining sub-options that are acceptable;

C. Calculate sub-option's characteristics, then partition sub-options into sets using these calculated characteristics, finally extremes of sets are used to eliminate unacceptable sets of combined options.

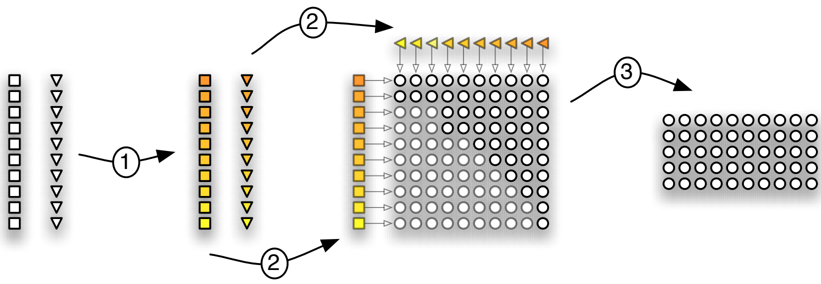
Figure F.7 demonstrates these three strategies for down selection showing the varying steps within each strategy. It should be noted that the later two strategies (B and C) can be more efficient than (A), particularly for large numbers of input items, but cannot be applied to all requirements. For example, a constraint expressed in terms of top speed can only be assessed after a combined Float-Move option has been generated. However, this requirement could be represented in a manner that allows it to be evaluated by comparing the sub-option's characteristics.

The first strategy (A), shown in Figure F.7a, is the simplest method. This strategy first combines the sub-options, then required characteristics are calculated for the combined option and checked against a specified constraint. Consequently, characteristics that are dependent upon several sub-options to be found using this strategy. The following key steps in this strategy are described in Figure F.7a:

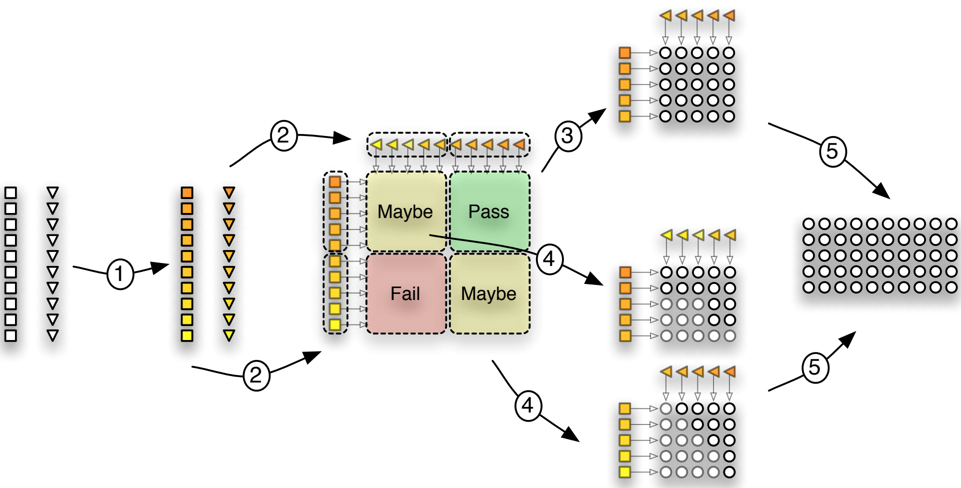
[9] At this stage new characteristic objects can be added and performance prediction methods employed to determine values necessary to check against the remaining constraints.



(a) Combine sub-options; then calculate performance



(b) Calculate performance of sub-options; then combine sub-options



(c) Calculate of sub-options; partitions into sets; use extremes of sets to eliminate unacceptable solutions

Figure F.7: Strategies for Down Selections for the Improved Implementation of the Library Method

1. Using sub-options (squares and triangles) generate all combined options (circles);

2. Calculate performance of combined options;

3. Discard unacceptable solutions (red circles).

The next strategy (B), shown in Figure F.7b, relies upon decomposing a top level requirement into characteristics that can be evaluated for the sub-options. For each potential combination of sub-options, these characteristics can be compared and, if the constraint is satisfied, a new option can be created. For example, a top level requirement for a certain maximum speed could be decomposed into power at top speed (for the Float sub-option) and maximum power (for the Move sub-option). These two characteristics could then be assessed by a constraint, such as ensuring the required power at top speed is less than the maximum installed power. The characteristics only have to be calculated once for each sub-option. The key steps are shown in Figure F.7b:

1. Calculate performance of sub-options;

2. Examine possible combinations of sub-options (squares and triangles), then generate combined options (circles) where sub-option criteria satisfy constraints;

3. Retain acceptable combined options.

The final strategy (C) also uses sub-option characteristics to down select sub-options but in addition sub-options are grouped into sets, allowing the number of comparisons to be minimised, as illustrated in Figure F.7c. By partitioning the two sets of sub-options into subsets, using the values of the characteristic being examined, the number of comparisons can be radically reduced, since the extremes of the partitioned subsets can be compared to determine whether combining the sub-options, from these subsets, will produce acceptable or unacceptable combined options. The key steps are:

1. Calculate the performance of sub-options;

2. Partition sub-options into subsets, then examine the limits of the subsets to determine if sub-options would satisfy constraints;

3. For subsets that clearly satisfy the constraints, generate all combined options;

4. For a subset that may satisfy the constraints, examine each option individually, then generate combined options (circles) where sub-option criteria satisfy constraints;

5. Retain acceptable combined options.

As an example of this strategy has been applied to the case of a maximum speed requirement. For two options M and F representing the Float and Move sub-options the power available and required can be found using the functions $pow_{avail}(\ldots)$ and $pow_{req}(\ldots)$. Acceptable solutions should satisfy the following relationship:

$$pow_{avail}(M) > pow_{req}(F)$$

Therefore, the limits of unacceptability for Move and Float options ($\mathbf{M}$ and $\mathbf{F}$) can be found from:

$$\begin{aligned}(pow_{req})_{min} &= min\,[pow_{req}(\mathbf{F})] \\ (pow_{avail})_{max} &= max\,[pow_{avail}(\mathbf{M})]\end{aligned}$$

Clearly, acceptable Float options require less power than the largest power available from the Move options. Similarly, acceptable Move options should provide more power than the minimum power required by the Float options. Using these two conditions the subsets of acceptable float and move options can be identified.

$$\begin{aligned}\mathbf{F}_{acc} &= \mathbf{F}(pow_{req} < (pow_{avail})_{max}) \\ \mathbf{M}_{acc} &= \mathbf{M}(pow_{avail} < (pow_{req})_{min})\end{aligned}$$

And then combined to determine the set of combined options ($\mathbf{C}$).

$$\begin{aligned}\mathbf{C} &= \mathbf{F}_{acc} \times \mathbf{M}_{acc} \\ &= \{(f, m) \mid f \in \mathbf{F}_{acc} \,\text{and}\, m \in \mathbf{M}_{acc}\}\end{aligned}$$

Depending on which of the three different approaches is applied, the number of required operations will be significantly different. Table F.3 illustrates the significant variation of down selection and performance prediction steps that occur for the three down selection strategies (these values illustrate a library containing 1000 sub-options for each function and half the combined options are assumed to be acceptable). This table shows a marked decrease from strategy A to B and C in both the number of times the performance prediction method must be applied and also the number of comparisons that must be performed.

F.1.5 Production–Deduction–Induction Compliance in the Improved Implementation

Section 4.3.1 drew attention to March's Production–Deduction–Induction model of the design process that illustrated the advantages of externalising the definitions of inductive, deductive and abductive reasoning [March 1984]. This model shows a process whereby knowledge contained within or produced by the design process is made explicit, thus allowing a more appropriate application of that knowledge to that design problem. Section 5.3.5 detailed how the addition of new knowledge could take place in the context of a Library

Table F.3: Example of the Variation in Sub-Option Combination and Performance Prediction for different Down Selection Strategies

Down Selection Strategy	A	B	C
Performance Predictions	1,000,000	2,000	2,000
Sub-Option Comparisons	1,000,000	1,000,000	500,000[a]
Comparisons of Sub-Option Sets	–	–	4
Sub-Option Combinations	500,000	500,000	500,000[b]

[a] Of which 250,000 are acceptable.
[b] With 250,000 from the comparison of sets and 250,000 from the comparison of sub-options.

Based Design approach. In the specific implementation presented here, that addition of knowledge could take one of two forms:

- Design information can be added to the library as new Item objects, representing known design solutions or options;
- Design knowledge, that makes use of point design information, can be added to the library using new performance prediction methods.

Separating the process of adding design information from existing design knowledge allows the designer to progressively develop a more complete design library in an open manner. Design information need not be complete, since appropriate performance prediction methods can be used to fill any gaps, using estimations based upon preexisting data from the library.

The approach presented here has been deliberately made adaptable and provides an architecture allowing different performance prediction methods to be used to manage the addition of design knowledge. Methods ranging from simple equations, an interpolation method and artificial neural networks have been explored during the development of the improved implementation. Other methods, such as expert systems, would appear to be compatible with the Library Based approach but have not been investigated in the course of this research.

F.1.6 Implementation Technical Details

The improved implementation has been developed using the object-oriented programming language Objective-C [Apple 2008b]. This provides the implementation's core design generation, evaluation, storage and selection methods. There are distinct benefits arising from adopting this development language. Employing Objective-C allows access to a powerful data-management framework called Core Data [Apple 2008a]. This allows the objects forming the data model to be easily created, modified and deleted. Objects can also be archived in a number of different storage formats, including a SQLite database. By employing a database based storage format, very rapid search operations can be performed. However, there are overheads associated with creating new objects within the database, so for the combine actions (where millions of objects may be created, examined and discarded) lightweight proxy objects are employed. These proxy objects are equivalent in functionality to the objects within the library but are not immediately added to the library when created.

Objective-C allows the definition of operations that contain an encapsulated task. These operations are added to a queue of remaining operations that are executed when computer resources become available [Apple 2008c]. Dependencies can be defined between operations, in which case the operations execution will be delayed until all preceding operations are completed. On a computer with multiple processors the program will execute operations in parallel where possible, speeding the overall completion of the process. Figure F.8 illustrates how the exploratory implementation's Actions (as described in Section F.1.3) can be easily subdivided into several operations allowing them to be executed in parallel. By creating a large number of simple operations, work can be split efficiently over several processors, reducing run time. The Library Based approach is particularly well suited to representation via many apparently sequential actions which can be completed in parallel. Other design approaches require a significant number of iterations where the complete results of one iteration must be obtained before the next iteration is started. Therefore, they are less amenable to similar parallelisation which prevents the application of one approach commonly used to increase the speed of an implementation at run time.

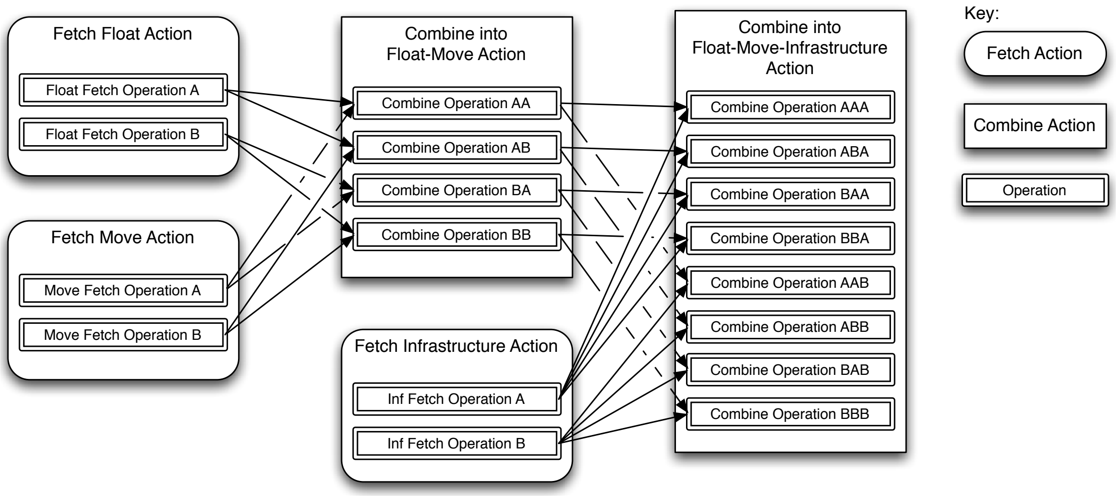


Figure F.8: Evaluating Actions using Multiple Operations in the Improved Implementation of the Library Method

F-Script [Mougin and Ducasse 2003; Mougin 2006], a lightweight scripting layer, specifically designed for interactive access to Objective-C objects was also utilised. F-Script provides a high-level language for object manipulation, allowing the user to easily manipulate and query whole sets of options. This provided a concise interface for exploring the items within the library.

The implementation includes the following methods to undertake performance prediction: simple arithmetic operations; summation of sub-option characteristics; interpolation [Lourakis 2008]; and artificial neural networks [Nissen 2003]. Examples of the types of performance prediction methods employed in the model are presented in Table F.4.

Table F.4: Example Performance Prediction Methods

Performance Prediction Method	Characteristic	Input Data
Interpolation	Top Speed	• Ship resistance at different speeds (Float); • Machinery maximum supplied power (Move).
Sum Sub-Item Characteristics	Weight	• Sub-Item weights.
Artificial Neural Network	Resistance	• Training data set composed of key dimensions and Resistance–Speed data; • Key dimensions; • Speed range.

F.2 Exploring the Performance of the Improved Implementation

The performance of the implementation varies depending on several factors including:

- Number of Item objects within the library;
- Number of Characteristic objects within the library;
- The arrangement of Action operations in the tool;
- The requirements specified by the designer (and how these can be applied through the strategies discussed in Section F.1.4).

This section explores the performance achieved by the improved implementation. It is divided into three sub-section that address different areas of performance:

- The effect of different sized libraries on the time required to retrieve options from the library (Section F.2.1);
- The effect of different numbers of input items upon the total time required to generate combined options (Section F.2.2);

- The speed of the different performance prediction methods within the current tool (Section F.2.3).

To explore the performance in these different areas a range of libraries of differing sizes were created. Four functions were defined in the library, a parent function and three sub-functions. For each of the three sub-functions the number of ITEMS objects generated were varied between 100 and 50,000 to see the effect of library size upon execution speed. Consequently, the size of the total library varied from 300 to 150,000 ITEM objects. For each ITEM objects in the library seven CHARACTERISTIC objects were created. Five of these CHARACTERISTIC objects had a single value, randomly distributed between zero and one. The remaining two CHARACTERISTIC objects had four values corresponding to different conditions[10].

Table F.5 contains details of the total number of ITEM, CHARACTERISTIC and VALUE objects in the library in each case. The exploratory implementation, described in Chapter 6 contained 1944 Float sub-options, 618 Move sub-options and 36 Infrastructure sub-options or 2598 options in total. If each of these sub-options were represented by an ITEM object then a library whose size was between that of library A and B from Table F.5 would be required to describe a case equivalent to that described in Chapter 6. Libraries C and D show how the implementation's performance changes as the library grows both 10 and 50 fold compared to Library B.

Table F.5: Details of Example Libraries

	Library Identifier			
	A	B	C	D
ITEM objects per Function	100	1,000	10,000	50,000
Total ITEM objects	300	3,000	30,000	150,000
Total CHARACTERISTIC objects	2,100	21,000	210,000	1,050,000
Total VALUE objects	27,300	273,000	2,730,000	13,650,000

F.2.1 Fetch Action Durations With Library Size

Three different fetch actions (termed 'fetch 1', 'fetch 2' and 'fetch 3') filtered the options from the library using four constraints. The constraints were set so 6.25%[11] of the ITEM

[10] These value were defined as a linear series beginning with a random base number between zero and one; i.e. 0.45, 1.45, 2.45 & 3.45.

[11] The constraints stated that the values of 'characteristic 1', 'characteristic 2', 'characteristic 3' and 'characteristic 4' must be greater than 0.5. As the value for each characteristic was defined as a random number between zero and one, there is a 50% chance of the option being accepted against any single constrain. Given that there is a probability of 0.5 of a single option passing one constraint, then the probability of a single option passing all four constrains is $0.5^4 = 0.0625 = 6.25\%$.

objects from the library were accepted. For each constraint the time required to search the library for acceptable ITEM objects was found.

The improved implementation performs a query in the following manner:

1. Constraints are filtered to find those that match the characteristic types defined in the function;
2. Constraints matching the function's characteristic are formatted as a query then sent to the database back end[12];
3. Process the information returned from the database and retrieve the acceptable ITEM objects;
4. Any remaining requirements can then be used to filter the acceptable ITEM objects[13].

The duration of the three fetch actions for the different sized libraries are shown in Table F.6. Figure F.9 shows the how the total duration of the fetch action changes with the number of ITEM objects per function. While the time required to search the library of ITEM objects increases as the library grows in size, examining the average duration per ITEM objects it can seen to be relatively constant. The fetch action duration per ITEM object shows a good agreement (with variation in the average fetch action duration per ITEM object within 7%) for the three larger library sizes (B, C and D). The smaller library (A) shows a slightly large fetch action duration per ITEM object which can be attributed to other background tasks[14] occurring on the computer which cause slight variations in the total execution time of the fetch action.

F.2.2 Combine Action Durations with Library Size

Once the fetch actions have retrieved the acceptable options from the library a combine action was used to create a number of combined ITEM objects from the fetched ITEM objects. No additional constraints were added at this stage. The durations of the two

[12] A query is a structured statement containing a number of conditions that initiates a search in a database and returns matching object. Significant changes in database performance may occur for different query structures. An exploration of database response time for different queries discovered the most efficient query mechanism. The elements of this query are listed below in the order they are checked against the items stored in the database:

a) Characteristic objects with a function matching the Action's function;
b) Characteristic objects with a characteristic type matching the characteristic type of the constraint;
c) Characteristic objects with a value that satisfies the constraint value defined in the constraint.

The items associated with these characteristic objects are then found and returned.

[13] This is necessary to ensure that any constraints filtered at step 1 (and therefore not part of the query sent to the database) are satisfied.

[14] These tasks could include either one off activities within the program such as creating areas to store the ITEMS retrieved from the library, peculiarities of the fetch process in relation to small data sets or other back groups activities associated with the operating system. These are more apparent when examining the smaller library, as any delay will have a large impact per ITEM object.

Table F.6: Durations for Fetch Actions for Variations in the Size of the Library

		Library Identifier			
		A	B	C	D
Item Objects per Function		100	1,000	10,000	50,000
Fetch 1	Item Objects Remaining	19	81	630	1,515
	Duration (sec)	0.106357	0.134239	1.716199	3.124275
Fetch 2	Item Objects Remaining	15	65	650	1,532
	Duration (sec)	0.040363	0.150128	1.099820	5.026420
Fetch 3	Item Objects Remaining	12	71	613	1,603
	Duration (sec)	0.042783	0.198888	1.771236	4.950645
Average Fetch Action Duration (sec)		0.063167	0.161085	1.529085	4.367113
Average Fetch Action Duration Per Item Object (sec)		2.11×10^{-4}	5.37×10^{-5}	5.10×10^{-5}	5.82×10^{-5}

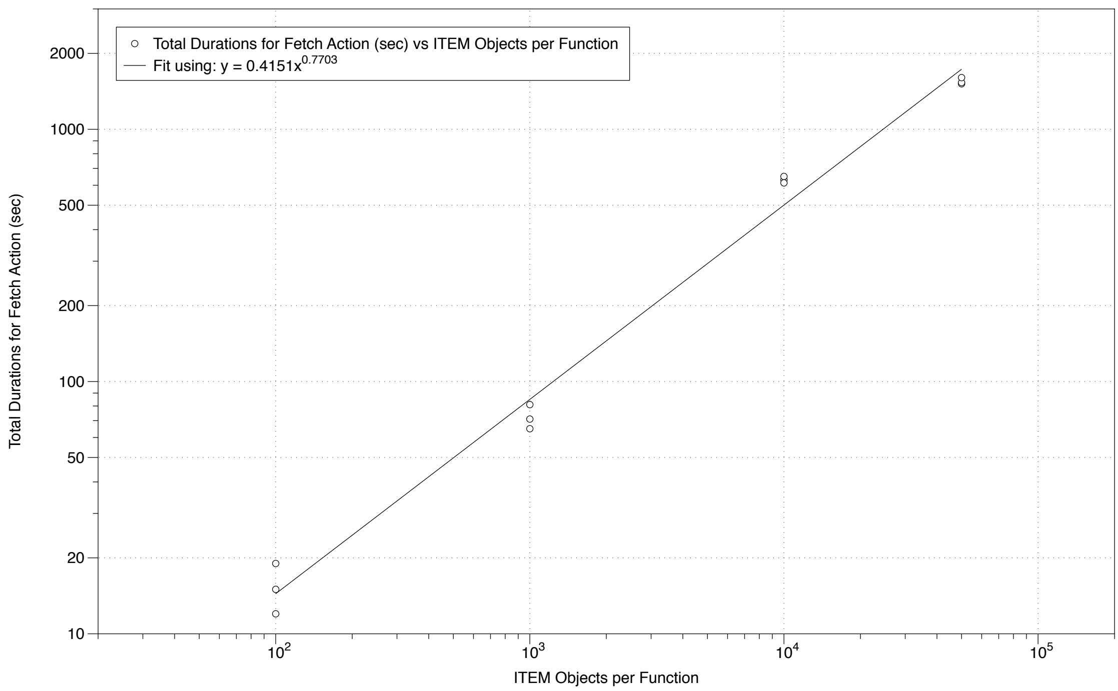


Figure F.9: Relative Durations for Fetch Actions for Variations in the Size of the Library combine actions for the different sized libraries are shown in Table F.7. The time taken for each combination action is relatively consistent; it increases in proportion to the number of ITEM objects until the number of new combined ITEM objects reaches a large number (i.e. +4,000,000). At this point the storage requirements for the new ITEM objects exceed the capacity of the computer's random access memory, and the computer must fall back to (slower) hard disk storage. A limit of 5,000,000 ITEM objects for any combine operation was used to prevent excessive run-time once large numbers of viable ITEM objects (i.e. >5,000,000 per combine action) are generated.

Table F.7: Durations for Combine Actions for Variations in the Size of the Library

	Library Identifier			
	A	B	C	D
Fetch 1 Remaining Sub-Options	19	81	630	1,515
Fetch 2 Remaining Sub-Options	15	65	650	1,532
Fetch 3 Remaining Sub-Options	12	71	613	1,603
Options Output by Action Combining 1 & 2	285	5,265	409,500	2,320,980
Duration of Action Combining 1 & 2 (sec)	0.004	0.017	1.630	17.505
Average Combine Action Duration (sec)	1.44×10^{-5}	3.21×10^{-6}	3.98×10^{-6}	7.54×10^{-6}
Options Output by Action Combining 1–2 & 3	3,420	373,815	5,000,000	5,000,000
Duration of Action Combining 1–2 & 3 (sec)	0.014	1.617	36.138	171.572
Average Combine Action Duration (sec)	4.25×10^{-6}	4.35×10^{-6}	7.22×10^{-6}	3.43×10^{-5}

F.2.3 Duration of Different Performance Prediction Types

The variation in speed of the different performance prediction techniques found in the tool is explored in this section. While a number of different approaches to performance prediction are possible, five representative approaches implemented in the current tool are presented here:

- Performance prediction using pre-calculated values, where pre-calculated values stored in the library are used to retrieve acceptable ITEMS;

- Performance prediction using values calculated by addition, where a simple addition operation acts upon the pre-calculated values stored in the library to then produce a new value;
- Performance prediction using values calculated by simple interpolation, where the performance prediction method performs a simple linear interpolation based upon the two closest pre-calculated values already stored in the library;
- Performance prediction using values calculated by complex interpolation, where the performance prediction method fits a given function to the pre-calculated values stored in the library. This function is then used to interpolate a value at a specific point;
- Performance prediction using values calculated by artificial neural network.

The durations of these different actions for the different sized libraries are shown in Table F.8. These values correspond to time required to assess each item in a library containing 10,000 Item objects. For each Item a value is calculated by the performance prediction method and then checked against a constraint. The data-management framework used in the improved implementation features intelligent caching, allowing data retrieved from the library is held in more quickly accessible memory. Consequently, Table F.8 contains the duration required for the different performance prediction methods in the case where data must be retrieved from the library and data is stored in this more quickly accessible cache.

Table F.8: Variation in Performance Prediction Speeds for a Library Containing 10,000 Items

Performance Prediction	Duration of Performance Prediction (sec)	
Type	with Data Retrieval	using Cached Data
Pre-calculated Values	5.932178	1.148290
Calculated by Addition	6.008430	1.154642
Calculated by ANN	6.038313	2.961134
Calculated by Simple Interpolation	14.348913	6.689205
Calculated by Complex Interpolation	14.057554	2.969440[a]

[a]The complex interpolation method stores the values of the fitted function leading to an increase in speed compared to the simple interpolation method.

When retrieving data from the library, the five performance prediction methods (shown in Table F.8) can be split into two broad types. The performance prediction methods that use pre-calculated values, values calculated by addition and values calculated using artificial neural network only require a limited number of values to be retrieved from the library. Therefore, only a small number of time consuming queries of the database housing the library must be performed. In comparison, the two interpolation methods require a large number of condition values to be retrieved from the library leading to a longer run time as many time consuming database actions are performed. However, after the values have been fetched from the database by the performance prediction method a number of techniques can be used to speed its execution. The simple interpolation method displays some increase in speed by using values that are stored (or cached) in the computer random access memory, as opposed to re-fetching the values from the database. The complex interpolation method stores the function that was fitted to the library data when it was first run, which leads to a considerable increase in speed for later runs.

Appendix G

Hullform Comparison and Selection During Requirement Elucidation

This appendix was published as a conference paper entitled “Hullform Comparison and Selection During Requirement Elucidation in the Concept Stage of the Ship Design Process” at the Tenth International Marine Design Conference (IMDC) in Trondheim, Norway, May 2009.

Hullform Comparison and Selection During Requirement Elucidation in the Concept Stage of the Ship Design Process

Tim P McDonald[1] and David J Andrews[1]

ABSTRACT

The importance of requirement elucidation, in shaping both the customer's needs and initial solutions during the concept stage of the design process, is well recognised. It is also the case that alternative hullform styles can bring distinct performance benefits in achieving emerging requirements. However, design methods and tools currently available do not facilitate the ready exploration of alternate hullform styles during the process of requirement elucidation. This paper outlines a library based ship concept design tool intended to assist the designer with hullform selection in the initial exploratory stage of the ship design process. In addition to discussing both the need for a tool and the reasoning underlying the tool's development, this paper also describes potential applications of the tool in concert with other design methods, such as the UCL derived Design Building Block Approach.

KEY WORDS

Requirement Elucidation; Concept Design; Hullform Selection; Data Retrieval (Library Based Tool)

INTRODUCTION

Current concept design tools and methods have been developed around individual vehicle styles (e.g. Monohulls, SWATHS, Trimarans) (Andrews 1997). They essentially adopt a standard approach to the design problem: synthesise a design solution from a set of (proposed) requirements; assess the solution's performance using analysis tools; and, compare the resultant performance with these initial requirements to assess the solution's viability and efficiency. Any perceived deficiencies or excesses require an updated design to be synthesised and reanalysed, until what is perceived to be a satisfactory solution is obtained. A large amount of work may be performed if more than one hullform type is being examined and this could be considered highly ineffective, given those configurations rejected could be considered as absorbing nugatory effort. Given the limited resources available in the concept stage of the ship design process, a method allowing the designer, not just to explore many hullform styles but to do so concurrently, is seen to be highly desirable.

The paper presents an approach that enables different hullform styles to be concurrently examined, providing a multi-vehicle concept design approach to ship concept design. First, the problem of hullform comparison and selection is discussed, in light of the difficulties inherent in the design process to meet complex ship requirements. From this discussion, attention is drawn to the activity of requirement elucidation, seen as a key feature of such ship concept design. Next, the limitations of applying current ship design methods to the hullform selection problem are highlighted. Current design tools are seen to be limited in their ability to rapidly assess multiple hullform types and are therefore seen to restrict the desire to undertake requirement elucidation in as open and divergent manner as possible at the initial stages of ship design.

An alternative approach to addressing the hullform selection problem at the initial stages of ship design is outlined, together with an example implementation. This approach is composed of two key elements: a novel approach to ship concept design, employing a library based design method that makes use of selection, combination and rejection; and, a support system describing the relevant domain, in the form of a performance prediction framework. The amalgamation of these two elements into a new concept design tool, together with some sample output is presented. This is followed by consideration of the integration of the proposed approach with other ship concept design methods. It is concluded that the proposed tool will enable a designer to rapidly examine multiple hullform options, which would significantly assist ship concept designers in the requirement elucidation process.

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THE HULLFORM COMPARISON AND SELECTION PROBLEM

Hullform Comparison and Selection in the Ship Design Problem

This section considers why hullform selection is not easily accomplished using current initial ship design approaches and how the need for consideration of hullform alternatives meets the perceived needs for initial ship design.

The Ship Design Process and its Difficulties

The initial concept phase of the ship design process is concerned with the clarification of the requirement and the development of an outline design to meet these requirements. Gale (2003) describes how this is achieved—particularly for naval combatants—through a series of studies, which in many cases, are developed into a single concept design. The concept phase is a critical stage when the majority of the cost of the final solution is committed. Tibbitts and Keane (1995) state that over seventy percent of a ship's final cost is determined in the Concept Phase, even though only some five percent of the design definition has been undertaken.

The initial stage of the concept phase, is termed by Andrews (1994) as Concept Exploration to denote the 'unrestrained exploration' of possible means of meeting the initial (vaguely conceived) needs for the new design. This exercise is intended to explore the solution space and should include modifying existing ships, packaging the perceived capability in different manners and exploring high and low technology options to determine the region of interest in the solution space and, consequently, should be both exploratory and divergent, allowing the designer to consider radical alternatives.

Customer Needs

The customer's needs are usually key to initiating the concept design process. One of the designer's primary concerns is to properly understand these needs and the likely requirements that arise from them. The designer must also ensure that constraints originating from other participants in the design process are recognised, questioned and then collectively agreed following a proper concept elucidation process (Andrews 2003b). As a corollary of these tasks, the designer must also ensure the customer is made aware of the impact of all the likely and significant requirements upon any emergent design (Rawson and Tupper 2001):

> "The earliest stages are typically a debate with the owner, proposing various ways in which the owner's wishes could be fulfilled, matching the operations envisaged to the investment that would be necessary to perform them."

Andrews (2003b) has identified this key process as being requirement elucidation, which should drive this concept stage of the ship design process. The process of elucidating the design requirements can only be achieved through design. It is also important to recognise that any limitations of the designer's adopted design method or tools may well constrain the exploration by failing to consider alternative hullform styles and hence limit a thorough exploration and elucidation of the customer's true needs.

Hullform Style in the Concept Design Process

The term style has been coined (Brown and Andrews 1980; Andrews 1984) to describe the broad characteristics of a ship design solution, as a means of identifying important design issues distinct from the classic concerns of naval architecture (i.e. S^4—stability, speed strength and seakeeping), namely aspects such as robustness or low signatures. This paper focuses upon a key decision on style that occurs at the outset of the design process, the decision on the hullform style. In this case, style is being used to differentiate hullform types into categories such as Monohull, Catamaran and Trimaran. Hullform style is of significant interest as it has a large impact upon the vessel's performance. Furthermore, the selection of hullform style has an obvious and major impact on the remainder of the design process.

The selection of hullform style is of considerable interest and has been explored by many authors. Various authors (Andrews 2001; Eames 1981, 1985; MoD 2005b) provide qualitative assessments of different hullforms. Other published work has attempted to perform quantitative analysis of different hullforms to find those best suited to a given role. This has taken the form of comparative studies exploring the effect of changes of hullform type on the solution's characteristics (Lavis and Rogalski 1989; Sadden and Nisbet 1998; Broadbent and Kennell 2001; McDonald et al. 2004; NATO 1987, 1997, 2004).

When developing comparisons of this type, various complications emerge, as revealed in the following comment from Lavis and Rogalski (1989) describing the difficulty of ensuring that comparative studies are objective:

> "[The issue of objectivity] led to the development of a joint parametric study…between the United States (US) and West Germany (GE). One problem that occurs when comparisons are made is that many people become

involved because of the magnitude of the project and each has his own analytic methods, preferences and biases. As a result different standards, margins and practices are often employed so that each of the hullforms are not always designed to the same standard, resulting in the proverbial "apples and oranges" comparisons. Even the use of computerised design-synthesis models does not always eliminate this problem since the programs are generally written by different people, or organisations, and for different purposes."

Counter to the need for an 'unrestrained exploration' in the initial stage of the concept phase, the designer is constrained by the decision making environment. Andrews (1981) identified three types of constraint on the ship design process: constraints directly on the design, constraints on the design process and constraints from the (wider) design environment. (Erikstad 1996) provides a supporting outline of the preliminary ship design 'task environment', which describes the set of constraints that apply in a 'prototypical preliminary ship design situation' and he highlights seven characteristics that are sources of difficulty. These have been grouped under three headings in Table 1.

Table 1: Sources of Difficulty in the Ship Design Process taken from (Erikstad 1996) and categorised

Complexity of Ships	Interdependencies and Analysis Limits	Complexity of Design
• *High cost of error* – errors are difficult and expensive to rectify as any changes must propagate through the whole design • *Strict time and resource constraints on the design process* - challenging procurement timescales result in the designer making decisions before fully understanding the problem • *Strong domain tradition* – the shared common understanding between interested parties masks some complexity but increases the difficulties of adopting novel solutions	• *Complex mapping between form and function* – the complexity arising from operating on the air-sea interface and the multi-functional nature of elements of the solution prevents the development of simple form-function mapping (and even if it were possible the legitimacy of such a mapping for ship design has been questioned (Andrews 2003b)) • *Shallow knowledge structure* – limited design knowledge is available, particularly for revolutionary designs	• *Predominantly "one-of-a-kind" and "engineering-to-order" solutions* – ship design is essentially a 'one shot' operation with little opportunity to learn by trial and error in a given design • *Multi-dimensional, partly non-monetary performance evaluation* – the procurement of ships relies upon the evaluation of many non-monetary performance characteristics where designer or customer judgment plays a key role

Given the difficulties outlined in Table 1 and the fact that they will be amplified if different hullform styles are to be explored, it is sensible to consider if there are any limitations in applying current design tools to the very early stages of ship design.

Current Design Methods

A comprehensive summary of recent ship design methods is presented in previous IMDC State of the Art Design Methodology reports (Andrews et. al. 1997 and 2006). Table 2 summarises what are seen to be the key limitations that arise when applying these methods to the selection of hullform style early in the design process.

Examining the types of ship design methods presented in Table 2 reveals that all six categories experience some limitations when applied to hullform selection in the early stage of the ship design process. However, the sources of these limitations vary between the six methods. The methods towards the top of the table experience limitations due to the inherent limits of human cognitive speed, and hence the speed of decision-making. The methods towards the bottom of the table suffer limitations arising from the simplistic nature of current machine based decision-making tools. These two different limitations imply that the issue of decision-making needs to be addressed.

Two extremes exist for decision-making methods: involved decision methods or detached decision methods. Involved decisions methods position the designer in a central decision making role. Detached decision methods employ a design tool that uses objectives and constraints to find a best solution. In general, involved methods enable the designer to gain a detailed understanding of the driving factors of a small number of solutions. In comparison, detached methods are amenable to automation and hence have the potential to be used to rapidly assess a large number of options to select a proposed solution. However, at the first stage of the design process the designer may actually wish to explore a large number of solutions to develop their understanding, as opposed to finding a single 'best' solution or obtaining a high degree of understanding of a single 'detailed' solution, given that requirement elucidation is unlikely to be resolved so early in the process.

Table 2: Perceived Limitations regarding Current Design Methods in Exploring Hullform Selection

Category	Example Methods	Limitations Regarding Hullform Selection
Traditional	• UCL Ship Design Exercise (UCL 2002)	As a designer led solution process it is difficult to consider more than one design concurrently.
Configuration Based	• Design Building Block Approach (SURFCON) (Andrews and Dicks 1997)	Reliant upon tools driven interactively by the designer hence speeding the design process. However, is limited in that only a single hullform option can be considered at a time.
Decision Making	• Decision Based Design • Multi Criteria Decision Making	Hard to apply to the early concept design process where the design process is both highly fluid and flexible.
Concept Exploration	• Concept Exploration Models	While well suited to the general process of exploring the solution space, limits on CEMs inbuilt synthesis methods limit their flexibility when comparing different styles of solutions.
Artificial Intelligence	• Expert Systems • Neural Networks	Most approaches are dependent upon stores of past design information so are inherently backwards looking. Recent research is exploring connecting these methods with generic prediction tools (van Oers et. al. 2006).
Optimization	• Single/Multi-Objective Genetic Algorithms	Difficult to correctly define objective functions (although current research is addressing ways of better incorporating non-numerical user input (van Oers et. al. 2008)).

Summary of Review of initial Hull Form Selection

The preceding review has discussed the importance of the designer fully exploring potential options as part of the concept phase of the ship design process. The difficulties presented earlier limit the number of options the designer can explore with constraints of time and resources. The process of requirement elucidation, which should underlie the early ship design process, adds a further complication. If the designer also wishes to consider different hullform styles—with widely varying characteristics and performance—then the problem becomes still more challenging.

Current ship design methods are seen as unable to provide an approach that adequately addresses the above issues. This is due to the fundamentally solution centric approach that they adopt, typified by the scheme outlined earlier. This approach can be seen to inhibit the exploratory phase of concept design, where the designer needs to rapidly explore as wide a range of options as possible.

At this point it is useful to consider what features ship designers have previously seen as required from a concept design tool. Betts' (2000) provides a useful checklist for the required capabilities of a warship design tool throughout the acquisition process:

1. Utilise data for assessment of performance, risk and through life cost;
2. Usable by knowledgeable design team;
3. Deal comparably with conventional and unconventional ship concepts;
4. Provide reasonable (preliminary) solutions;
5. Assist communications with design team and all stakeholders, especially those evolving the operational requirement.

While, Andrews (2003a) proposed that solutions produced by a preliminary ship design approach should be:

1. Believable solutions, meaning ones that are both technically balanced and descriptive;
2. Coherent solutions, meaning that the dialogue with the customer should be more than merely a focus on numerical measures of performance and cost, and should include visual representation;
3. Open methods, in that they are responsive to the issues that matter to the customer or capable of being elucidated from the customer or user teams;
4. Revelatory, so likely design drivers are identified early in the design process to aid effective design exploration;
5. Creative, in that options are not closed down by the design method and tool but rather alternatives are fostered.

These two sets of features capture the needs in the ship designer's tools, especially at the earliest stages in the design process when the choice of hullform has to be addressed.

Ideally, a design method or tool able to support hullform selection in the exploratory phase of the ship design process should assist the designer in understanding the customer's needs and hence assist the designer in the dialogue with the customer to elucidate the ship's eventual requirements. It should capture the impact of these evolving requirements on possible solutions. It should enable consideration of different hullform styles and not unduly constrain the designer to a limited selection of options. It must be sufficiently flexible to allow the addition of new information by the designer as it becomes available. It should aim to fulfil Betts' list of preliminary design tool needs and Andrews' list of creative ship solution characteristics. Finally, the method should strive to support different types of ship design novelty from simple development of an existing design through to technologically radical options (Andrews 1998).

THE PROPOSED METHOD OF INITIAL HULLFORM SELECTION

It is the contention of this paper that the requirements identified in the previous section can be satisfied through a library based ship concept design method, which is outlined in this section. This section then discusses the underlying philosophy that underpins the proposed design method and addresses the general approach adopted for performance prediction within the method. Finally, these two parts are brought together to describe the approach as a whole.

A Library Based Ship Concept Design Method

The proposed method is based upon a limited library of possible options describing a large number of possible ship designs. This library has to be constructed before the designer begins to search for potential options. The designer is then able to rapidly filter the options in the library to find those that satisfy the current design requirements. This allows the designer (and hence the customer) to gain a better understanding of the impact of any requirement upon the styles available to provide potential ship solutions.

The UCL design procedure used for the major postgraduate ship design module (UCL 2002) has a range of different ship synthesis methods, which have been drawn upon to create a large number of potential options to populate the library. After generating these options, the characteristics and performance of each option can be found and stored within the library, avoiding some time-consuming calculations once the designer then explores potential options.

The initial library needs to be broad enough to contain an array of options that will be of interest to the designer. However, it is apparent that the number of options within the library will quickly grow and soon become unmanageable. Considering a ship synthesized from ten input variables, each with ten possible values, implies a theoretical total of 10^{10} options (Erikstad 1994). Applying a process of decomposition and down selection can reduce the number of options stored within the library. If a ship option is decomposed into a number of sub-options then these could be stored in place of the ship option so that these sub-options could subsequently be combined to produce a far larger set of possible whole ship options, here termed 'combined options'.

Conceptually a combination operation can, if formulated carefully, be applied to a number of different sub-options in manner that should be blind to ship style. The options resulting from a combination operation will have characteristics or performance that depends on the sub-options. For some characteristics, the methods required to determine these characteristics will be simple to apply. For example, an assessment of the total weight or volume of a number of sub-options (representing specific sub-systems in the ship) can quickly and accurately determine the combined option's weight or volume. However, it is recognized that this approach simplifies the combination of different sub-options and risks failing to capture the real impact that combining two or more different sub-options has upon the combined option's characteristics. Thus for example the total propulsive efficiency depends upon several elements of the combined option and is also highly dependent upon sub-option styles. Improved prediction tools, targeted at specific aspects, could then partially offset likely losses of accuracy. Furthermore, this method could then feed into the remainder of the design process, where other design methods might better capture the impact of such effects on options that are of particular interest.

The decision upon the type of decomposition to employ is of central importance to this approach. A number of different approaches exist (such as weight group or system level breakdowns). However, for a method aimed at providing the designer with a means of evaluating different hullforms, the functional group breakdown adopted by Andrews and Dicks (1997) provides a number of advantages. Thus each option of the ship design is therefore decomposed into four functional groups: Float, Move, Operation (or Fight) and Infrastructure.

It is recognized that solutions will exist between the different combined options, as a result of the way they have been created from a number of sub-options selected from a discrete library. Additionally, there will be limits on the extent of the solutions space that sub-options within the library can represent. While these two factors lead to a considerable constraint on a library based method, there is scope to extend the method to enable other options to be considered, either between existing points in the library or at the extremes of the library. However, for simplicity this additional feature has not been developed further in this realisation of the library based concept design method.

The options from the library could be filtered via a number of different search mechanisms, such as those employed within database tools (Atzeni et. al. 1999). The power and speed of current search techniques should be familiar to any user of Internet search engines. By assessing precalculated characteristics and performance of the options a rapid down selection process could be easily implemented. Furthermore, if part of this down selection process occurs at a sub-option level, by making use of an appropriate subset of the current requirements, then this will significantly reduce the number of combined options that the method has to consider. The possible combinations of remaining sub-options could then be used to produce a set of combined options. Finally, the set of combined options, which meet the overall constraints and requirements, could then be found.

The constraints and requirements that are used to remove unacceptable combined options can be used to ensure the options are 'balanced' (i.e. a constraint on weight vs. displacement could be used to remove unbalanced designs). While, an iterative sizing method (such as (UCL 2002)) could be employed to rebalance the combined options, its drawbacks must be considered. Burcher and Rydill (1994) highlight the larger number of interdependencies occurring in even a simple four-component weight breakdown. As a consequence, the rebalancing process may be highly sensitive to these interdependencies when exploring a solution that departs from current practice. By using constraints to ensure the options are 'balanced', the rebalancing step is avoided and effort can be dedicated to exploring alternative options.

The characteristics of the particular stage of ship concept design that it is tailored towards will affect how the approach is developed. The fluid and exploratory nature of the concept stage of the design process means that new information is likely to arise. It should be easy to incorporate this information into the design tool – leading to a requirement for a mechanism, which allows the addition of new information. A library based method is well suited to incorporating new information as it arises during the design process. Options or sub-options can simply be added to the library.

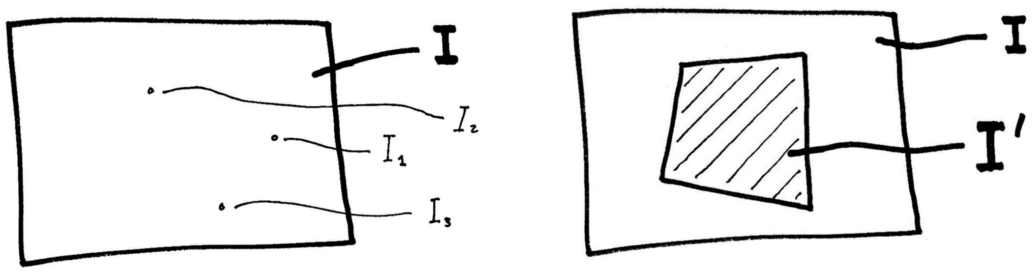
In summary this section suggests a library based ship concept design method could be employed to provide a simple mechanism to rapidly explore the impact of a set of requirements upon a whole ship solution. The proposed method uses a search and combination approach to explore potential options. This method avoids some of the difficulties present in design automation and optimization methods that aim to develop a single best solution. Rather, it aims to facilitate a better exploration of workable and unworkable options.

Comparison with Other Similar Methods

Of the seven categories of design methods presented in Table 2, the library based method presented here is most similar to Concept Exploration Methods (CEM) as proposed by a number of authors (Eames and Drummond 1976; Erikstad 1994; Molland and Karayannis 2001). CEMs allow the designer to explore a wide variety of potential solutions generated via a parametric synthesis process. CEMs generate these solutions at a whole ship level, while the proposed library base method does so by generating and combining sub-options. Additionally, the synthesis models used within previous CEMs have been limited to consider only one hullform style (with the notable exception of (Molland and Karayannis 2001)). The use of a library based model, as proposed in this paper, would give a clear distinction between the task of generating options for the library and the sequential exploration of these options. This task separation has the potential to free the designer from a single synthesis model, allowing options produced by a number of different synthesis models to be examined. There are also parallels between the simple search process employed in the proposed method and the mechanisms discussed by Yoshikawa (1979) in relation to his General Design Theories (GDT and GDT-Real).

On the Development of the Design Method

This section develops the approach underlying the library method from a simple definition, initially abstracted from the ship design problem. To begin, a continuous space **I** can be defined which contains all possible potential options (I_1,I_2,I_3,…), as shown in Figure 1(a); this space defines an infinite number of options. Any option from this set can be retrieved and its properties examined, either directly or using a suitable prediction method. If the infinite design space **I** were bounded by some arbitrary limits (representing the limits of current knowledge regarding the design space) a finite space will be obtained which will be denoted by **I'**, as shown in Figure 1(b).



(a) (b)

Figure 1: A comparison of (a) an Infinite Space *I* and (b) a Bounded Space *I'*

Ideally, a designer would obtain options directly from this space (i.e. the space could be described in terms of simple functions and then a solution obtained by solving these functions, using the requirements as an input). However, some characteristics of marine vehicles give rise to a discontinuous design space, which means it is impractical to evaluate potential options through simple continuous functions. A possible compromise is to represent the space through a number of discreet options. Unfortunately, as the space **I'** is continuous it will be described by an infinite number of options (I_1,I_2,I_3,…). However, if the options are restricted to a fixed number m distributed randomly across the space then a discrete design space $\mathbf{I}^*$ is obtained to describe the set of options being considered, as shown in Figure 2.

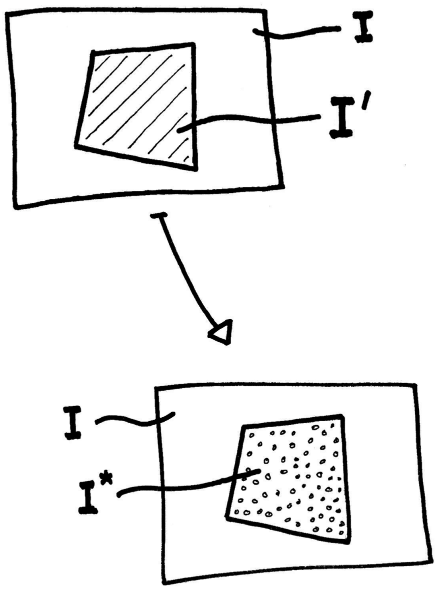


Figure 2: Bounded Space approximated via a limited set of solutions, $\mathbf{I}^* = \{I_1, I_2, I_3, \ldots, I_{m-1}, I_m\}$

This discreet set of options can be compared against a set of requirements to find the options that fulfil any requirements or constraints, discarding those that are unacceptable. This is similar to the approach adopted in previous concept exploration models (Eames 1976). However, in order to reasonably represent the solution space, the options must be distributed throughout the space with an appropriate level of granularity and this then leads to a large number of options to be considered.

One possible approach to this problem is to consider a mapping which could decompose a single option into a number of sub-options. The sub-options can then be combined to produce a far larger set of combined options. However, this approach depends upon the decomposition process the designer employs to obtain the sub-options. Considering a single option I from within the set $\mathbf{I}^*$, then by applying some mapping to decompose the option a number of sub-options could be produced. The case of a mapping able to decompose the option I into three sub-options (I_A,I_B,I_C) gives:

$$I \mapsto I_A, I_B, I_C$$

Before discussing the practicalities of constructing a mapping able to decompose an option, it is necessary to explore performance prediction for options.

Performance Prediction for Options

The performance and characteristics of any option can be thought of as properties (p_1,p_2,p_3,…) and are governed by relationships linking them to other properties of the option. For example, if the option under consideration were a monohull ship then the waterline length can be derived from other properties, as shown by the following well known relationship:

$$L = \frac{\nabla}{C_B BT} = f(\nabla, C_b, B, T)$$

Similar methods can be applied to predict or calculate other properties of interest (either the option's performance or characteristics). Some vessel properties are amenable to simple analytical relationships (i.e. small angle stability). Other properties must be evaluated through more complex methods (i.e. seakeeping) and such methods are typically difficult to apply in the early stages of the design process; since they require detailed information not normally generated in the concept phase. Furthermore it is hard to develop prediction methods that are robust, accurate and generalised with the limited information available. The difficulty in predicting these more complex properties has led to the generation of a range of empirical and semi-empirical performance prediction methods. Recent research (Maroju et. al. 2006) has explored developing prediction algorithms based upon the currently available information, in order to provide rapid predictions of some ship properties. A number of approaches, such as regression analysis and machine learning methods (i.e. neural networks), could be used to develop prediction methods that are easy to update.

In general, prediction methods can be thought of as determining the value of a property based upon other properties. If these properties are collected together in a vector **x**, then any property can be found via some function acting upon this vector:

$$p = f(\mathbf{x})$$

However, given the complexity apparent within any ship, the vector **x** will be very large. Additionally, for many properties **x** will contain redundant information, such as other properties that are unconnected or only weakly connected to the property under consideration. Current design methods draw out these important relationships. For example, the UCL MSc design procedure provides a set of equations linking the dimensions, mass and volume for a monohull warship (UCL 2002, 2004). By examining these equations, relevant relationships could be revealed.

Figure 3 collects together the key variables in the sizing equations taken from (UCL 2002, 2004). For each key variable listed along the top of the figure, the variables upon which it directly depends are indicated in the column below (using a • symbol). For example, the UCL sizing procedure defines draught through a relationship between displacement, volume and depth. The columns in Figure 3 have been arranged to collect variables in clusters of closely related properties. These clusters can be seen to match those used when decomposing a ship into functional groups (other authors have previously proposed applying decomposition in ship design without proposing a specific link back to functional groups (Tan and Sen 2001)). Additionally, a fourth cluster emerges describing whole ship characteristics, which are similar to general ship characteristics defined in (Andrews 1984). Current design methods, such as (UCL 2002), iterate the whole ship properties in this cluster until a balanced solution emerges.

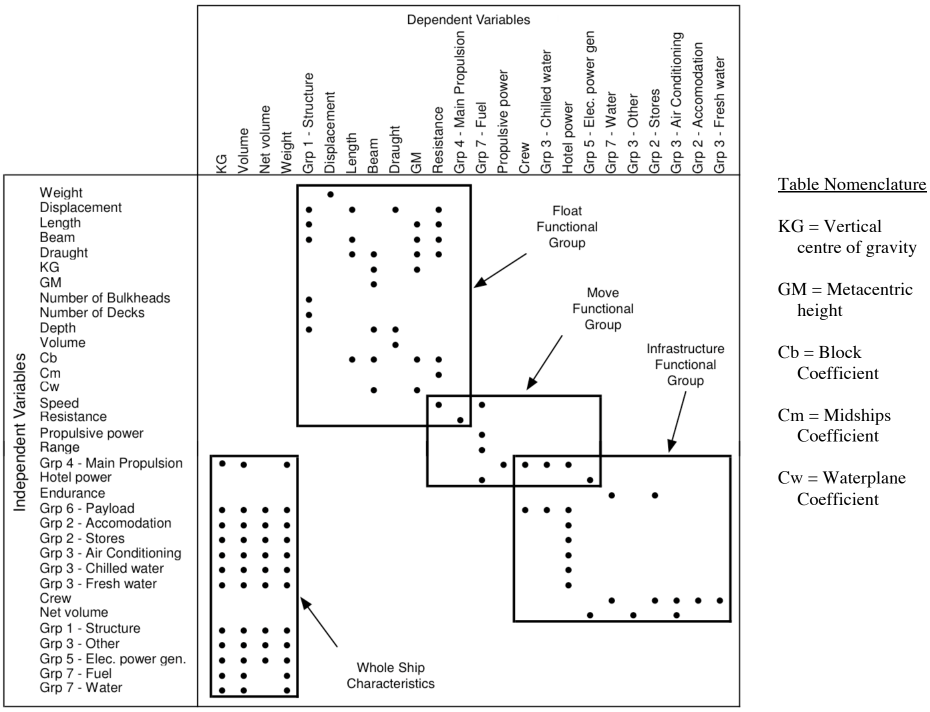


Figure 3: Clustered Relationships Between the Key Variable based upon data from UCL Ship Design Process (UCL 2002 & 2004)

A number of the properties that are more difficult to predict, such as resistance, can be seen to lie within a single cluster. If other complex prediction methods are considered some of these can be similarly constrained to a single cluster (i.e. seakeeping and large angle stability are predominantly dependent upon the hullform shape, displacement and the position of the vertical centre of gravity and hence are associated with the Float function). For those properties that are difficult to predict, it is sensible to pre-calculate and store their values within the library. In comparison, overall vessel properties are comparatively easy to evaluate (i.e. mass and volume are simple summations of scalar values) and so they can be rapidly determined from the properties of the sub-options that make up the combined option.

It is appreciated that there are other properties that will be far more difficult to predict. In such cases, an appropriate, fast calculating, prediction method will need to be applied in order to successfully determine the properties of interest. For example, to find the ship's seakeeping response, the prediction method should make use of both the hullform's hydrodynamic properties (a property of the Float function) and whole ship properties, such as vertical centre of gravity and radius of gyration. The ship's response could be determined through several methods, including: directly from pre-calculated hullform hydrodynamic properties (stored in the library) and the whole ship properties; by interpolating between values of ship response determined for different values of whole ship properties; or, from simple equations or empirical relationships, if available (e.g. Lloyd 1989, 1992). This shows how whole ship properties, affected by layout, will determine the ship's vertical centre of gravity. The majority of these difficult to predict properties appear to be driven by layout. For example, survivability is a strong driving factor in warship concept design. Current methods used to assess survivability require a highly detailed design definition to be produced. Consequently, the large number of interrelated variables under consideration will make the application of this decomposition method complex in such instances. However, some elements of the survivability calculation (i.e. blast propagation) could be performed at a functional group level. This would still provide additional useful information for a designer at the concept phase.

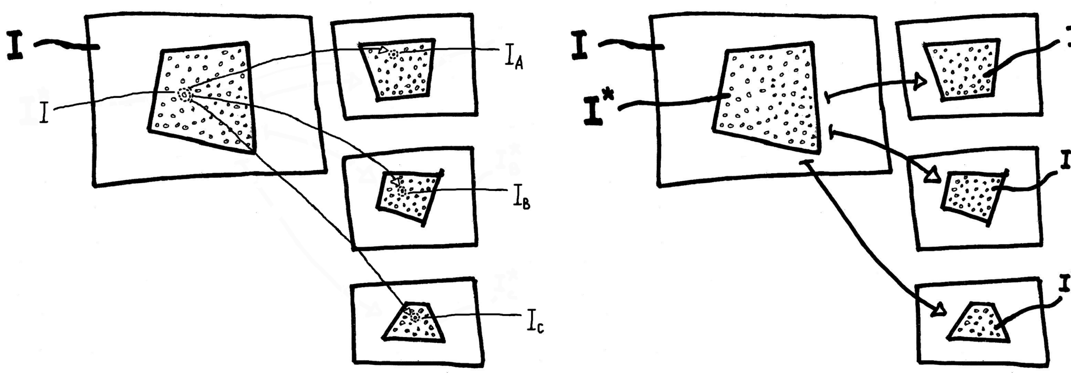
Decomposing Options

The concept of decomposing options via a mapping ($I \mapsto I_A, I_B, I_C$) was presented above. It is possible to generalise this mapping to the elements of a set $\mathbf{I}^*$, to give:

$$\mathbf{I}^* \mapsto \mathbf{I}^*_\mathbf{A}, \mathbf{I}^*_\mathbf{B}, \mathbf{I}^*_\mathbf{C}$$

This mapping is depicted graphically in Figure 4. This mapping can be inversed, therefore a collection of higher level options can be obtained from a number of sets containing sub-options:

$$\mathbf{I}^*_\mathbf{A}, \mathbf{I}^*_\mathbf{B}, \mathbf{I}^*_\mathbf{C} \mapsto \mathbf{I}^*$$



(a) (b)

Figure 4: (a) Decomposition of an Option (I) into three sub options (I_A, I_B, I_C) and (b) Decomposition of the Set ($\mathbf{I}^*$) into three Sub-Sets ($\mathbf{I}^*_\mathbf{A}$, $\mathbf{I}^*_\mathbf{B}$, $\mathbf{I}^*_\mathbf{C}$)

The previous section introduced the idea that clusters of connected variables could be grouped together to allow some ship characteristics or performance to be defined at a functional level. Therefore, by applying a decomposition approach based upon functional groups, an overall ship option could be separated into a number of functional groups sub-options, albeit with some connections between the groups for specific ship characteristics and performance.

Up to this point the discussion has been largely framed in terms of abstract options. At this stage it is useful to consider a ship based example. If initially a ship option S_S is considered then this option could be compared to a set of requirements to determine if it is an acceptable solution for this set. Requirements used to assess the ship option may include overall ship performance attributes, such as maximum range at a specified speed. Returning to the ship option and applying the reasoning presented earlier, S_S can be decomposed into four sub-options S_F, S_M, S_O and S_I (representing the Float, Move, Operations (or Fight) and Infrastructure functions respectively). Then we have $S_s \mapsto S_F, S_M, S_O, S_I$ and the inverse relationship $S_F, S_M, S_O, S_I \mapsto S_s$.

The designer wishing to develop a ship to meet a new collection of customer needs could define a new sub-option S_O that defines the Operations related systems required in the new ship. Alternatively, this could be expressed via a set of requirements R_O that includes the constraints imposed by the ship's payload (i.e. ensuring there is sufficient available space or crew to support the payload). In this case, feasible whole ship options excluding operations related system demands can be found by combining three sub-options S_F, S_M and S_I via a mapping such as $S_F, S_M, S_I \mapsto S_{(S\text{-}O)}$, where $S_{(S\text{-}O)}$ indicates the combined ship option excluding the payload demands. The remaining combined options can then be compared against the set of requirements R_O that includes the Operations related requirements.

Using an equivalent notation to earlier we can define sets containing the complete ship level options $\mathbf{S}_{(S\text{-}O)}$ and the three functional level options $\mathbf{S}_F, \mathbf{S}_M, \mathbf{S}_I$. As a first approximation, the number of possible options within the ship level set $\mathbf{S}_{(S\text{-}O)}$ depends upon the possible combination of functional level options from the sets $\mathbf{S}_F, \mathbf{S}_M, \mathbf{S}_I$.

Removing Options

If the number of options is dependent upon the possible combination of sub-options, then removing any functional group options from consideration will rapidly reduce the number of ship options in the set $\mathbf{S}_\mathbf{S}$. Two methods exist for removing sub-options from consideration. First, sub-options can be removed by comparing their characteristics against external requirements (e.g. the Float sub-option (i.e. hullform) is of insufficient length to accommodate the payload). Alternatively, sub-options can be removed from consideration by detecting incompatibilities across the sets of sub-options (e.g. a Float sub-option with insufficient available volume to accommodate a Move sub-options).

Incompatibilities can be examined for both an individual solution and for sets of options. For example, if the power required by a Float sub-option is less than the power supplied by a Move sub-option, these two options are incompatible (i.e. if a Float sub-option requires 30MW to attain the required top speed but a Move sub-option only supplies 20MW, then a combine option containing these two sub-options would be infeasible). Alternatively, the maximum power produced by a set of Move sub-options can be found and used to remove from consideration members of the set of Float sub-options that require a higher power to achieve the desired operating speed (i.e. if the largest maximum supplied power of a set of Move sub-options is 20MW then the Float sub-options requiring a greater power at the required top speed would be infeasible and can be removed).

New Options

For the design method proposed it should be possible to add new options to the original finite set of options. Options could be added directly at the top level (as part of the set $\mathbf{S}_\mathbf{S}$). Also a new option could be introduced at the functional level ($S_{\bar{F}}$), by combining this Float functional level option with existing Move and Infrastructure functional level options resulting in a new whole ship option ($S_{(\bar{S}-O)}$).

$$S_{\bar{F}}, S_M, S_I \mapsto S_{(\bar{S}-O)}$$

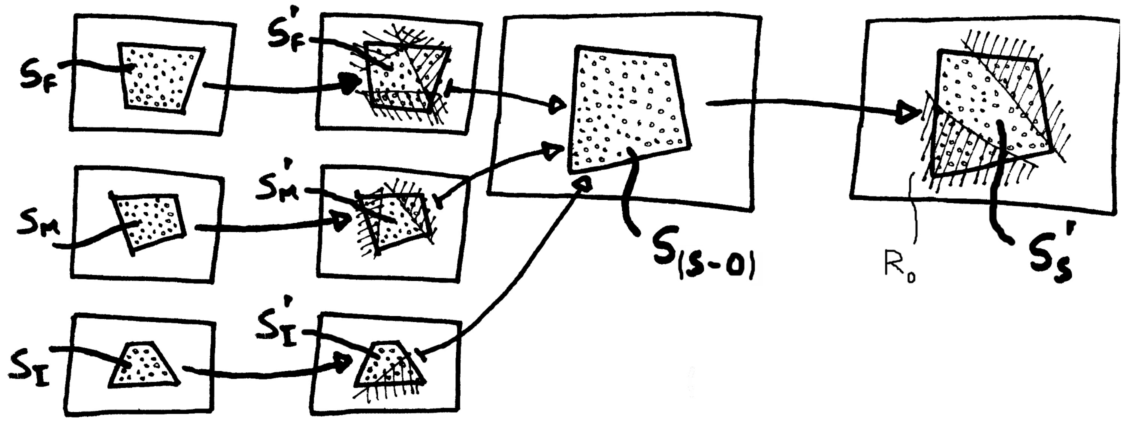
Note that at this stage the performance, and indeed the feasibility, of this new whole ship option is unknown. Therefore, the characteristics and performance of the new option must be assessed and compared against the requirements of interest to the designer to determine if it presents a viable option. This can take place at both the functional group level and the whole ship level. The earlier section on performance prediction for options suggested that a number of the top level characteristics are easy to assess. For example, performance characteristics, such as large angle stability, could be assessed using a GZ curve for the complete ship. This GZ curve can be determined from a SZ curve for the hullform (a property of the Float function) and the ships SG value (from the ship's vertical centre of gravity; a property of the combined option) using a standard method (Rawson and Tupper 2001). Furthermore, balance in the design could be determined at this point by ensuring a satisfactory relationship between the required and available values for characteristics, such as mass, volume and crew.

Not all characteristics will be amenable to a simple assessment; other approaches may have to be employed. The range of established analysis tools or methods able to address these more complex issues could be applied. Such tools and methods will inevitably incur increases in calculation time. As a result it is likely to be unattractive to employ these approaches to evaluate all potential options. Each option will belong to a larger set of similar options. As a result some characteristics can be determined or inferred from these other options. For some options in the library empirical data may be available. Alternatively, time-consuming analysis tools can be applied ‘off line’ to a selection of the options from the library, building a collection of firm data. From this collection of data approximate prediction methods could then be developed. These would then enable a rapid assessment of characteristics, although this assessment may be approximate. In terms of ship and functional group options, the database of available information on options or sub-options could be leveraged to rapidly predict the performance of a new option. The advantage of a store of this type is that, as new data is generated, it can be easily added into the library, leading to improvements in the prediction methods over time.

An example of the benefits of this approach arises when considering performance prediction for different hullform styles. For some hullform styles data will initially be sparse and any prediction methods developed only approximate, as is the case with current practice. However, if some form of modelling produced more performance information then the performance prediction tool could be readily updated. As the library of design options expands, performance prediction methods will be enhanced so improving the overall design process. The ability to simply incorporate new information into the prediction techniques can be seen in March’s terms as a cyclical process of abduction, deduction and induction (i.e. proposing a new design, finding its ‘real’ performance, then using this information to improve the available prediction tools). However, this approach’s suggestion of improving the overall design process by using a set of solutions differs from March’s description, which focused upon a single design (March 1984). Further, this could be done in a way that is clear to all design participants, since the information could be externalised by being incorporated into the library.

Illustrative Example of the Options Exploration Process

This section presents an illustrative example, at Figure 5, as to how the elements described in the previous discussion are combined into a process able to explore a library of sub-options to meet a set of requirements. At the left of Figure 5 are the sub-options for the three functional groups (**S_F**, **S_M**, **S_I**) that are stored within the library. These sub-options are then assessed against appropriate subsets of the requirements with those that fail being removed from consideration. The subsets of the requirements will differ between the functional groups, for example the Float sub-options that are to be removed from consideration could be initially down-selected on the basis of an overall length requirement, which would remove the inappropriate hullforms (e.g. those too long to meet docking constraints or those too short to accommodate the upper deck payload items). This would leave three sets of acceptable sub-options **S'_F**, **S'_M**, **S'_I** (Figure 5(b)). By employing the mapping discussed earlier, these three sets of sub-options could then be combined into a new set of combined ship options that exclude the payload demands **$S_{(S\text{-}O)}$** (Figure 5(c)). Again the appropriate requirements, including those originating from the payload demands R_O, could be used to remove further unacceptable options (e.g. those without enough available space to accommodate the payload, infrastructure and machinery). When assessing some of these requirements, performance prediction methods may need to be employed. In such cases an appropriate method can be used to account for major interactions between sub-options. In such cases, an appropriate correction (such as the seakeeping example given in the earlier performance prediction section) may need to be applied, in order to successfully complete the down selection. This will result in the final set of acceptable combined options **S'_S** (Figure 5(d)). This collection of options would then be presented by the tool to the designer.



(a) (b) (c) (d)

Figure 5: An Illustration of the Option Exploration Process

IMPLEMENTATIONS AND RESULTS

Example Implementations

Two test implementations have been developed: an exploratory Excel-based tool and an improved implementation developed using an object-orientated software framework. The exploratory implementation was developed rapidly as a proof of concept. A decision was made to use Microsoft Excel and Visual Basic to prototype the method. This prototype demonstrated that the underlying method could produce valid designs. During the development and use of the exploratory implementation, a number of issues were revealed. The two most significant ones were the lack of speed of the implementations and its lack of flexibility in managing options with different hullform styles. This led to the decision to develop a second implementation with significant technical improvements; this implementation is described below.

The improved implementation is built from a number of different objects. These objects act together to create a data model able to perform the key tasks that make up the proposed approach. The primary objects within the implementation are termed *Items* and *Characteristics*. The *Items* represent the different options. Each *Item* is related to a number of *Characteristics* objects that define the characteristics and performance of the *Item* (e.g. length, weight, power, etc). These primary objects are structured via a number of different relationships: *Items* are structured via *Functions* (such as Float, Move, Infrastructure and Whole Ship) & *Styles* (such as Monohull and Trimaran); *Characteristics* are structured by *Characteristic Types* (such as Length, Mass and Power supplied). Each *Item* is defined as belonging to a *Function*, which specifies its functional group (i.e. Float, Move…). *Items* can also be assigned a number of *Styles*; these provide a means of differentiating between different styles of solutions that occur in a single functional group (i.e. monohull or trimaran, both from the Float functional group). *Characteristics* are organised by *Characteristic Types*, which provide a means of identifying the characteristic. Each *Characteristic* can store a value (currently limited to a floating point number).

The process of searching the library for appropriate *Items* and combining these to form new options is performed by a number of *Actions*. *Actions* are split into two types: *Fetch Actions* that retrieve *Items* from the library and *Combine Actions* that generate new options from the combination of sub-options belonging to a number of input actions. These two types can be combined into a hierarchal tree of *Actions* with *Combine Actions* as branches and *Fetch Actions* as leaves. Both types of *Actions* allow requirements or constraints to be used to filter the options; specifically an option's characteristics are checked to ensure that a characteristic exists that satisfies a particular constraint (e.g. using a minimum length constraint to examine a float option's *Characteristics*, searching for a *Characteristic* with a *Characteristic Type* of 'length' and a value that satisfies the constraint).

For some options, specific characteristics will depend upon the value of the option's (or sub-option's) other characteristics. In these cases a *Performance Prediction Method* can be used to calculate the value rapidly. As discussed earlier, the performance prediction methods included in the implementation have been limited to those which are quick to run and can be updated easily (akin to current preliminary ship design 'rules of thumb'). The applicable performance prediction methods are limited using the style of a specific *Item* as a guide.

Implementation Details

The improved implementation has been developed using the object-oriented programming language Objective-C (Apple 2008a). This provides the implementation's core design generation, evaluation, storage and selection methods. There are distinct benefits arising from adopting this development language. Employing Objective-C allows access to a powerful data-management framework called Core Data (Apple 2008b). This allows the objects forming the data model to be easily created, modified and deleted. Objects can also be archived in a number of different storage formats, including an SQLite database (Apple 2008b). By employing a database based storage format, very rapid search operations can be performed to fetch *Items* objects, whose *Characteristics* meets a set of requirements. F-Script (Mougin and Ducasse, 2003), a lightweight scripting layer, specifically designed for interactive access to Objective-C objects was also utilised. F-Script provides a high-level model for object manipulation, allowing the user to easily manipulate and query whole sets of options. To undertake performance prediction, the implementation includes the following methods: simple arithmetic operations; summation of sub-option characteristics; interpolation (Lourakis 2008); and artificial neural networks (Nissen 2003).

Example Case Explored using the Implementation

The improved implementation was used to explore a library of data describing a frigate in the 3500-6000 tonnes displacement range. This library was generated using a number of simple UCL design tools (UCL 2002, 2004). Sub-options were generated at the functional group level for the Float, Move and Infrastructure groups from simple parametric equations (UCL 2002, 2004). Then using a set of requirements, describing both the performance the ship must attain and the payload the ship must support, the available options were constrained to a set of feasible options able to meet the performance requirements.

Library Data Generation

For the Float functional group, sub-options were generated from six input variables: displacement; overall hull density; hull depth; block coefficient; an assumed vertical centre of gravity; and superstructure volume fraction. The values of these variables were selected randomly but constrained to lie within specific ranges (e.g. the displacements considered ranged from 3500-6000te). From these six variables by applying hydrostatic and stability considerations, the remaining significant hullform characteristics were determined. From these, characteristics values for the mass (M_{float}), volume (V_{float}) and cost (C_{float}) of each Float sub-option were found using adapted UCL Ship Design Exercise equations (UCL 2002, 2004). With the hullform's characteristics now fixed, two performance analysis methods were applied: the required propulsive power for a number of ship speeds was determined (Holtrop 1984); and an estimate of the hullform's seakeeping performance was found using Bales simple method (Walden 1983).

For the Move functional group, sub-options were generated from three input variables. Two of these variables defined the solution's two prime movers (from twelve possible alternatives) and a third variable defined the amount of fuel carried. Each complete Move functional option was developed using the assumption that the propulsion train was constrained to consist of two propellers driven via appropriately sized reduction gearboxes. The data used to generates these sub-options was based upon that available from commercial sources and the UCL equations (UCL 2004). From these three variables the following data was obtained: mass (M_{move}); volume (V_{move}); and cost (C_{move}) together with values of power and fuel consumption for different machinery loads.

For the Infrastructure functional group, sub-options were generated from input variables describing the number of personnel onboard and required stores endurance, in days. The sizing equation also required a value of ship's net volume (representing the ventilated space within the ship). For simplicity this was assumed to be constant, for the purpose of this demonstration. By adding an additional input variable, different values of net volume could be easily considered. From these variables, values were obtained for the mass (M_{inf}), volume (V_{inf}) and cost (C_{inf}) of the Infrastructure functional group.

The current sizing equations utilise simple relationships to determine characteristic values from a limited set of inputs. This is recognised as being of limited utility as many stylistics choices cannot be represented through the current sizing equations. For example, performance prediction of multi-hullform Float sub-options cannot be assessed using the current sizing equations. Similarly the current sizing equations do not enable the assessment of different possible architectures for the distributed systems within Infrastructure sub-options. Further work, intended to better capture the impact of these different stylistic choices upon the different sub-options, is currently ongoing.

Downselect Steps in the Example Case

Applying a functional group breakdown enables the designer to consider the functional groups as distinct options. Options can be initially examined at a functional group level, acceptable options can then be combined to form whole ship options, provided that any resulting whole ship options are checked to ensure they meet all necessary requirements, in terms of both the ship's performance and those arising from the payload.

Once the initial library of Float, Move and Infrastructure options has been developed, the following steps were undertaken:

- Fetch functional group options from the library;
- Downselect the options for a functional group using designer selected criteria derived from requirements;
- Combine acceptable Float and Move options to create Float-Move options;
- Down select Float-Move options using designer selected criteria derived from requirements;
- Combine remaining Float-Move options with Infrastructure options to form Float–Move–Infrastructure options;
- Downselect Float–Move–Infrastructure options using designer selected criteria derived from requirements (including payload/operations requirements) to give the final whole ship options.

The steps listed above were defined as a number of *Actions* within the implementation. The flow of information between these *Actions* is shown in Figure 6. The different *Actions* are denoted in the figure by the boxes with bevelled corners.

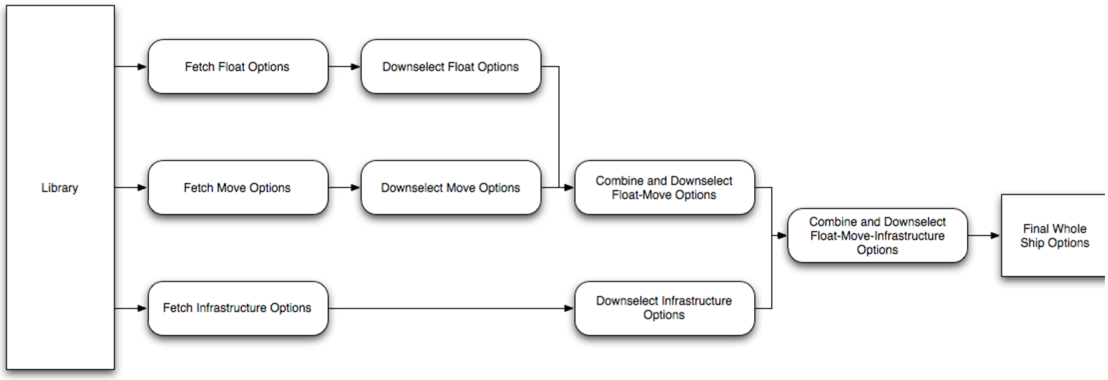


Figure 6: Flow of Information between the Steps in the Design Method

Fetch Action for Retrieving Float Options, Move Options and Infrastructure Options

The first step in the solution process involved retrieving the Float functional group options from the library. These options were then downselected using a number of input requirements. The three requirements used in the example for this downselect were: 'Draught < 6*m*', 'Length < 160*m*', 'Beam < 20*m*' and 'Power at a Speed of 30*kts* < 55*MW*'. The draught, length and beam requirements are representative of potential constraints on the ship due to docking limits. The powering requirement is representative of a potential requirement intended to limit Move group solutions to a lower powers and hence costs. This step reduced the initial 1898 Float functional group options to 477 options considered to satisfy the requirements.

Similarly, options retrieved from the library were down selected from the Move and Infrastructure functional groups. Initially 616 Move functional group options where generated, of which 544 remained after the downselect process. The requirements used for the downselect included propulsive power requirements obtained from examining the power required by the remaining Float options to achieve the required top speed. Similarly, 36 options for the Infrastructure functional group were retrieved from the library. These were downselected using requirements originating from the demands of the payload and mission, which resulted in 8 acceptable options. The requirement originated from the crew required to support the payload and the total required stores endurance.

Combine Action to create Combined Float-Move Options from Float and Move Options

At this stage there was sufficient information to proceed to combine the Float and Move functional group options. All possible combinations of the remaining Float and Move options were generated and then simple additional calculations used to assess the maximum speed and a speed-range profile. This combination of 476 Float group options and 544 Move group options created over 250,000 combined Float–Move options.

With the combined options available another set of downselections was undertaken with a new set of criteria. In this case the requirements used for this downselect were 'Range at 15*kts* > 11,500*nm*' and 'Top speed > 29.5*kts*'. This downselect process reduced the number of combined Float–Move options from over 250,000 to 7179 options.

Combine Action to create Combined Float-Move-Infrastructure Options from Float–Move and Infrastructure Options

The final combination step in Figure 6, combined the downselected Infrastructure option with the remaining combined Float–Move options. As before the different possible combinations were produced and then simple calculations used to determine the important overall characteristics of each generated option. By combining the 7179 Float–Move options with the 8 Infrastructure options over 57,000 combined Float–Move-Infrastructure options were generated. The overall characteristics assessed consisted of a value for the cost of each option together with mass and volume values for the options remaining available, from these a comparison was made to ensure the demands of the payload were met. Values for the remaining options available mass ($M_{avaliable}$) and volume ($V_{avaliable}$) were found by subtracting the total mass and volume of the three functional groups from the displacement (Δ) and volume (V) provided by the Float functional group (i.e. $M_{avaliable}=\Delta - (M_{float} + M_{move} + M_{inf})$ and $V_{avaliable}=V - (V_{float} + V_{move} + V_{inf})$).

Having produced the complete set of combined options available, a final set of downselections was undertaken to obtain the final solutions. In this case the requirements used for this downselection were 'Available Mass > 330*te*'; 'Available Volume > 2,160m^3'; and 'Cost < £150m'. This downselect step resulted in excess of 76,000 initial combined Float–Move-Infrastructure options being reduced to 51,142 whole ship options that fulfil the requirements.

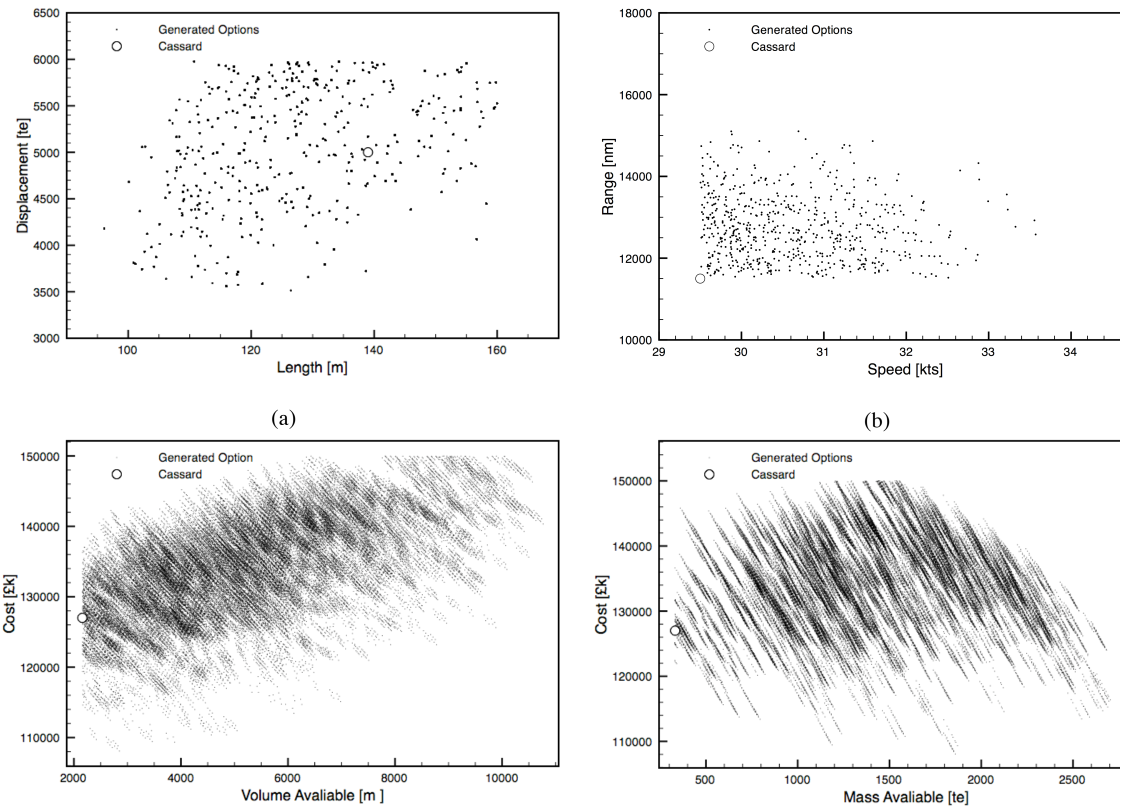
Presentation of Results

Example Output

To explore the remaining 51,142 options performance and characteristics, the options generated by the exploratory implementation were compared against two designs produced by traditional design methods. The results of one of these comparisons are presented in Figure 7. In this case the design selected for comparison was the French Navy's CASSARD Class Destroyers (Type F70 – DDGHM); this design is referred to as the 'Cassard' design. As only a limited amount of information is available via public sources (Saunders 2003) some of the ship's characteristics were estimated using ratios derived from similar ships (Brown and Andrews 1980; UCL 2004). The four different sub-figures that make up Figure 7 have been selected to show how the number of acceptable options change through the process described in the previous section, progressing from Figure 7a (which presents the Float sub-option characteristics) to Figure 7d (which presents the combined whole ship option characteristics).

Figure 7a shows the displacement and length of both the generated solutions and the 'Cassard' design. In terms of the functional breakdown, displacement and length are both characteristics of the Float sub-options. The small number of points on this graph is due to only a limited number of the original Float sub-options being able to fulfil the complete set of requirements. The original 1898 float options were reduced down to some 150 acceptable options by the three downselect actions detailed in the earlier section describing the example case explored using the implementation. The point representing the 'Cassard' design can be seen to lie in the centre of these points.

Next, Figure 7b shows the different options' top speeds and the options' endurance in terms of nautical miles at a cruise speed of 15kts. The point representing the 'Cassard' design can be seen to lie at the bottom left corner of the points representing the solutions. This is to be expected as two of the requirements used to downselect these solutions—the maximum speed of at least 29.5 knots and a range of 11500*nm* at a speed of 15 knots—are the quoted performance of the 'Cassard' design.



(a) (b)

(c) (d)

Figure 7: Example Outputs Compared Against the Cassard Design

Finally, Figures 7c and 7d show characteristics of the complete ship options. In these two charts the mass and the volume available are plotted against the combined cost of the options' Float, Move and Infrastructure groups. The point representing the 'Cassard' design can be seen to lie on the left of the points representing the generated options, indicating other options which satisfy the constrains are possible, although a majority of these are calculated to be more costly than the 'Cassard' design using the UCL comparative costing algorithms.

The above example demonstrates the methods ability to develop a number of whole ship options by combining a number of sub-options belonging to different functional groups. During this process a set of requirements, input by the designer, were employed to remove unacceptable options. The remaining options were then used to generate figures, such as those shown in Figure 7. These figures demonstrated that a number of viable alternative options exist for the set of requirements. This example has demonstrated how the tool has enabled an exploration of the solution space suited to the initial stage of the ship concept design process. However, for this exploration to be useful to the designer this must take place over a short timescale. Therefore, the required run time of the developed implementation is of interest.

Run Times

An important consideration of any ship concept design tool is the speed of execution. The following provides an indication of the duration of each step for the case described above. The code was run on a 2.4 GHz Apple MacBook Pro laptop. The total execution time was 34.35 seconds. Times for the individual actions are indicated in Figure 8.

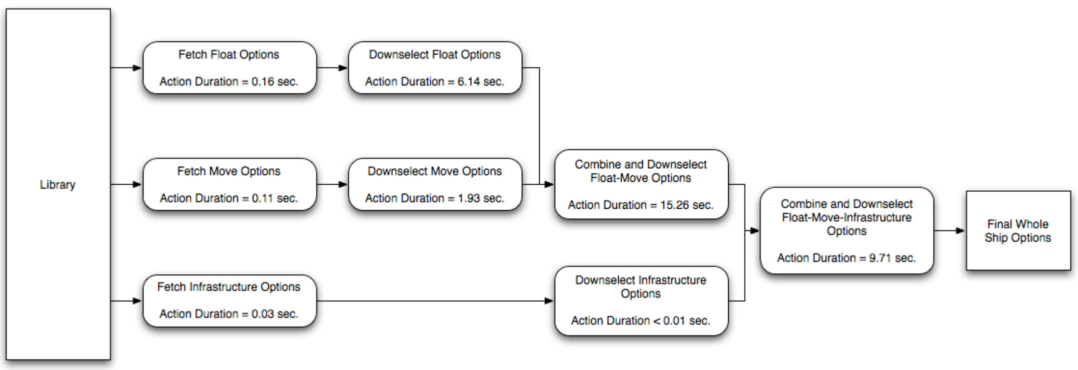


Figure 8: Total Duration for Different Actions for the Example Ship Concept Investigation (see Figure 6)

The simple selection and combination steps underlying the process are amenable to being run in parallel. The options initially fetched from the library can be split across a number of equivalent operations required to perform the actions but which could be executed concurrently. Table 3 shows the variation in total run time for different library sizes and the number of concurrent actions. The second column, with two concurrent actions, indicates that the case presented above was run in parallel across two CPU cores in the test machine. In the one concurrent actions case, the program was limited to only running on a single CPU core.

Two cases are presented in Table 3: a simple case and a complex case. The simple case corresponds to the example case described above (assessing a potential 42,090,048 possible options from an initial 1891 Float sub-options, 36 Infrastructure sub-options and 616 Move sub-options). The complex case is similar to the simple case but with four times the number of options in each of the Float, Move and Infrastructure sub-groups (assessing a potential 2,693,763,072 possible options from an initial 7592 Float sub-options, 144 Infrastructure sub-options and 2464 Move sub-options), namely, a 64 fold increase in total possible solutions.

Table 3: Total Run Times for the Illustrative Example of the Proposed Approach

	Concurrent Actions = 1	**Concurrent Actions = 2**
Simple case	34.4 seconds	27.1 seconds
Complex case	545.6 seconds	464.9 seconds

DISCUSSION

The Flexibility of the Proposed Method

The simple and flexible method underpinning the library based tool results in the ability to manage arbitrary information. This then should allow different hullform styles to be readily compared. This has not been demonstrated in this paper, as currently there is a lack of available data or appropriate analysis tools to create a required library of sub-options, particularly for the Float function. The necessary work to demonstrate this extension is being undertaken. This will then be added to the library so that a full demonstration of this method able to deal with different hullform styles, is intended to be presented in a future paper.

Speed of the Implementation

The results from Table 3 show that partitioning the selection of options into a number of operations, which are then performed concurrently, can significantly reduce the total run time. The library based tool allows the rejection of infeasible options at a sub-option level. This results in the overall run time increasing more slowly than would have been expected if a simple brute force method had been employed to examine all available options. For the simple and complex cases described in Table 3, where the latter is equivalent to an increase in the number of potential options by sixty-four times, the library based tool demonstrates an increase in run time of only fifteen to sixteen times.

The Issue of Integrating the Proposed Tool with the UCL Design Building Block Approach

Referring back to the end of the second section where Andrews' and Betts' lists of features necessary to fully support the ship design process were summarised, it can be seen that the proposed library based design system is able to provide many of the required features. However, Andrews' requirement to demonstrate coherent solutions via a visual representation is not currently satisfied by the method outlined above. While a visualisation system of some type could be employed to directly display the solutions, significant resources would be required to undertake this integration. An alternative to this approach—which provides a number of other benefits—is to combine the library based method with a graphically based ship design approach. The following illustrative example demonstrates how the proposed tool could be used in collaboration with a different design method, namely a design being developed using the Design Building Block (DBB) approach (Andrews and Pawling 2006).

Figure 9 shows how the outputs of a library based ship design tool could be used to better inform a designer. In this case by providing a number of outlines illustrating the gross geometry of the remaining options (i.e. those generated by the library based tool, which have not been removed by the requirements input by the designer). As the designer begins to define and develop the design (in this case using a configuration driven tool), additional constraints will emerge, such as the need to position payload items along an upper deck, which is likely to define a minimum ship's length or machinery layout, which could drive the ship's beam at certain longitudinal locations. Such constraints could then be used to further develop and constrain the feasible options, providing the designer with assurance that the design 'makes sense'.

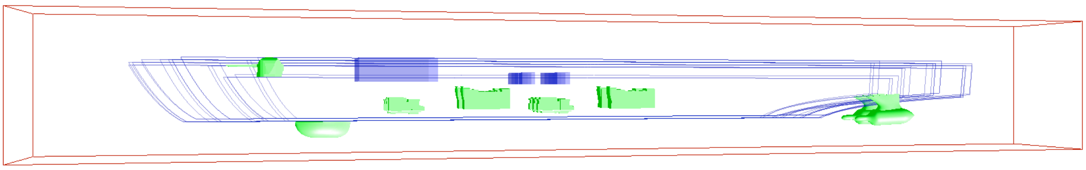


Figure 9: Illustrative Example of Integration of the Proposed Library Method with the UCL Design Building Block Approach (showing example DBB and outlines from library data)

Upon comparing the developed library based ship design method (incorporating the proposed link to a configuration based design method) against Andrews' list of features necessary for a preliminary ship design approach, the following conclusions emerge.

1. Believable solutions: the options proposed by this method satisfy a set of constraints defined by the designer. These constraints can be used to ensure that the developed solutions are technically balanced;
2. Coherent solutions: Integrating the method presented here with a visual representation (as suggested by Figure 9) allows a dialogue with the customer beyond simple numerical measures of performance and cost. The combined Library and Design Building Block approach allows the designer to present the customer with an integrated configuration based design, but at the same time allows the rapid exploration of options using the library;
3. Open methods: The rapid manner in which the options are downselected is highly amenable to alteration allowing the designer to respond quickly to issues generated by the customer. Coupling this method with an appropriate visualisation and design tool should allow rapid exploration of options, improving the design team's responsiveness to customer queries and hence achieve Requirements Elucidation aims (Andrews 2003);
4. Revelatory: The proposed method and tool can be used to quickly identify numerical design drivers early in the design process. But to realise its full potential, as an aid to effective design exploration, links to the DBB approach need to be developed further;
5. Creative: Compared to other ship design methods, by allowing the designer to postpone the selection of hullform style, this method allows options to remain open until later in the design process, fostering the development of alternatives that may have previously been discarded and can be seen to encourage a Set Based Design approach (as outlined by Lamb in the Preliminary Ship Design Methodology section of (Andrews et. al. 2006));

CONCLUSIONS

The design method developed in the course of this research adopts a simple, but flexible approach to the ship concept design. This approach is seen to be worthwhile due to the unique challenges occurring in the requirement elucidation stage of the ship design process compared to the remainder of the ship design process. In tailoring the Library based method to tackle these front end challenges, it is seen to be of limited utility for the full design process (i.e. particularly for the detailed development of the design for approval and manufacture). Rather, the proposed method is well suited to assisting the designer in more comprehensively exploring the solution space in the preliminary stages of the ship design process.

Further Work

While the approach outlined is considered to provide a first step towards a tool able to better satisfy Betts' and Andrews' aspirations for a tool or method to support the very early stages of the ship concept design process, The following further work is seen as desirable for the library method to become a practical tool in the preliminary ship design process of naval ships:

- Demonstrate the application of the tool to a problem with a wide range of hullform styles. This would ultimately require a range of comparable designs to be developed as discussed earlier.
- Explore methods of presenting the designer with relevant information on the hullform styles that remain potential options.

REFERENCES

ANDREWS, DJ. 'Creative Ship Design'. RINA Transactions, volume 123:pp. 447–471, 1981.

ANDREWS, DJ. 'Synthesis in Ship Design'. Ph.D. thesis, University of London, 1984.

ANDREWS, DJ. 'Preliminary Warship Design'. RINA Transactions, volume 136:pp. 37–55, 1994.

ANDREWS, DJ. (Ed) 'State of the art report on design methodology', International Marine Design Conference (IMDC'97), Vol 2, pp137-187, Newcastle, UK, 1997

ANDREWS, DJ. 'A Comprehensive Methodology for the Design of Ships (and Other Complex Systems)'. Proceedings of the Royal Society A, volume 454:pp. 187–211, 1998.

ANDREWS, DJ. 'Adaptability - The Key to Modern Warship Design'. RINA Warship 2001 - Future Surface Warships. Royal Institution of Naval Architects, London, 2001.

ANDREWS, DJ. 'A Creative Approach to Ship Architecture'. RINA International Journal of Maritime Engineering, volume 142, September 2003a.

ANDREWS, DJ. 'Marine Design - Requirement Elucidation rather than Requirement Engineering'. Eighth International Marine Design Conference (IMDC'03). 2003b.

ANDREWS, DJ and DICKS, C. 'The Building Block Design Methodology Applied to Advanced Naval Ship Design'. Sixth International Marine Design Conference (IMDC'97). 1997.

ANDREWS, DJ, (Ed.), KEANE, RG, LAMB, T, SEN, P and VASSALOS, D. 'State of the Art Report: Design Methodology'. Ninth International Marine Design Conference (IMDC'06), volume 1. Ann Arbour, Michigan, May 2006.

ANDREWS, DJ and PAWLING, R. 'The Application of Computer Aided Graphics to Preliminary Ship Design'. Ninth International Marine Design Conference (IMDC'06), volume 2. Ann Arbour, Michigan, May 2006.

APPLE. 'The Objective-C 2.0 Programming Language', Apple Inc., Cupertino, CA, http://developer.apple.com/documentation/Cocoa/Conceptual/ObjectiveC/ObjC.pdf, 2008a

APPLE. 'Core Data Programming Guide', Apple Inc., Cupertino, CA, http://developer.apple.com/documentation/Cocoa/Conceptual/CoreData/CoreData.pdf, 2008b

ATZENI, P, CERI, S, PARABOSCHI, S, and TORLONE, R. 'Database Systems: Concepts, Languages and Architectures'. McGraw-Hill, London, 1999.

BETTS, CV. ‘Development in Ship Design from a Naval Perspective’. Seventh International Marine Design Conference (IMDC’00). Korea, 2000.

BROADBENT, C and KENNELL, C. ‘Monohull, Catamaran, Trimaran and SES High Speed Sealift Vessels’. RINA Fast 2001. Royal Institution of Naval Architects, Southampton, UK, September 2001.

BROWN, DK and ANDREWS, DJ. ‘The Design of Cheap Warships’. Proceedings of the International Naval Technology Expo 80,. Rotterdam, 1980.

EAMES, MC and DRUMMOND, TG. ‘Concept Exploration – an Approach to Small Warships Design’. RINA Transactions, volume 118:pp. 29–54, 1976.

EAMES, MC. ‘Advances in Naval Architecture for Future Surface Warships’. RINA Transactions, volume 123:pp. 93–118, 1981.

EAMES, MC. ‘Future Naval Surface Ship’. US Naval Engineers Journal, 1985.

ERIKSTAD, SO. ‘Improving Concept Exploration in the Early Stages’, Fifth International Marine Design Conference (IMDC’94). 1994.

ERIKSTAD, SO. ‘A Decision Support Model for Preliminary Ship Design’, Ph.D. thesis, NTNU, The University of Trondheim, 1996.

GALE, PA. ‘Ship Design and Construction’, ‘The Ship Design Process’, Volume 1, Chapter 5, pp. 5.1–40. (Ed. T. Lamb) The Society of Naval Architecs and Marine Engineers, Jersey City, NY, 2003.

HOLTROP J. ‘A statistical reanalysis of resistance and propulsion data’. International Shipbuilding Progress, 31(363):272–276, November 1984.

LLOYD, ARJM. ‘Seakeeping: Ship Behaviour in Rough Weather’, Ellis Horwood Limited, Chichester, UK, 1989

LLOYD, ARJM. ‘The Seakeeping Design Package (SDP)’, RINA Transactions, volume 134:pp. 161–180, 1992.

LOURAKIS, MIA. ‘levmar: Levenberg-Marquardt nonlinear least squares algorithms in C/C++’, http://www.ics.forth.gr/~lourakis/levmar/, 2008

LAVIS, DR and ROGALSKI, J, WILLIAM W. ‘The Promise of Advanced Naval Vehicles for NATO’. Technical report, SNAME Chesapeake Section, The Society of Naval Architects and Marine Engineers, 1989.

MOLLAND, AF and KARAYANNIS, T. ‘Development of a Concept Exploration and Assessment model For Advanced fast Marine Vehicles’. Sixth International Marine Design Conference (IMDC'97), 1997.

MARCH, L. ‘The Logic of Design’. Developments in Design Methodology, editor N Cross, pp. 265–276. Wiley, New York, 1984.

MAROJU, S, SYAMSUNDAR, S, DELORME, M, VASUDEVAN, S, DATLA, R, PENNOTTI, M and BRUNO, M. ‘A value focused approach to ship design synthesis, analysis, and selection’. World Maritime Technology Conference 2006 (WMTC2006). The Institute of Marine Engineering, Science and Technology, London, 2006.

MCDONALD, TP, GREIG, AR and RUSLING, S. ‘A Comparative Study of the US Navy Littoral Combat Ship’. RINA Conference on the Design and Operation of Trimaran Ships. Royal Institution of Naval Architects, London, 2004.

MOD. ‘Warship Engineering Management Guide (WEMG)’. Technical report, Sea Technology Group, Defence Procurement Agency, Ministry of Defence, Abbey Wood, March 2005b.

MOLLAND, AF and KARAYANNIS, T. ‘Development of a Concept Exploration and Assessment Model for Advanced Fast Marine Vehicles’. Sixth International Marine Design Conference (IMDC’97). 1997.

MOUGIN, P and DUCASSE, S. ‘OOPAL: Integrating Array Programming in Object-Oriented Programming’. Proceedings of the 18th ACM SIGPLAN conference on Object-oriented programing, systems, languages, and applications. 2003.

NATO. 'Assesment of Point Designs - Volume II: Detailed Assesment'. Technical report, NATO Armament Group Special Working Group, 1987.

NATO. 'The Application of Costing and Operational Effectiveness Methods for the Selection of Hull Types'. Technical report, NATO Armament Group Special Working Group, March 1997.

NATO. 'NATO-PfP Working Paper on Small Ship Design'. Technical report, NATO Naval Group 6, 2004.

NISSEN, S. 'Implementation of a Fast Artificial Neural Network Library', Department of Computer Science University of Copenhagen (DIKU), 2003, http://fann.sf.net

RAWSON, KJ and TUPPER, EC. 'Basic Ship Theory'. Butterworth-Heinemann, Boston, 5th edition, 2001.

SADDEN, JA and NISBET, C. 'Are Two Hulls Better than One (or Three)?'. RINA Warship '98 - Surface Warships. Royal Institution of Naval Architects, London, 1998.

SAUNDERS Stephen, editor. 'Janes Fighting Ships 2003-2004', Section 'Cassard Class'. page 226. Janes Information Group, 2003.

TAN, K. & SEN, P. 'The Application of a Decomposition and Reuse Approach in Marine Design'. Practical Design of Ship and Other Floating Structures, 2001

TIBBITTS, T and KEANE, RG. 'Making Design Everybody's Job: The Warship Design Process'. US Naval Engineers Journal, 1995.

VAN OERS, B. 'Applying First Principles Tools in Naval Ship Design' RINA Warship '06 - Surface Warships, Royal Institution of Naval Architects, London, 2006.

VAN OERS, B, STAPERSMA, D and HOPMAN, H. 'Issues when Selecting Naval Ship Configuration from a Pareto-Optimal Set', 12th AIAA/ISSMO Multidisciplinary Analysis and Optimisation Conference, September 2008

WALDEN, DA. 'Extension of the Bales Seakeeping Rank Factor. In 20th American Towing Tank Conference, volume 2, pages 1037–1045, Hoboken, New York, 1983.

UCL. "MSc Ship Design Procedure." Department of Mechanical Engineering, University College London, 2002.

UCL. "MSc Ship Design Data Book." Department of Mechanical Engineering, University College London, 2004.

YOSHIKAWA, H. 'General Design Theory and its Application to Categorization of Ship Design'. International Symposium on Advances in Marine Technology, pp. 69–89. Trondheim, Norway, 1979.

Appendix H

Case IV: Background Information

This appendix contains background data supporting Case IV detailed in Section 7.4 of Chapter 7.

H.1 Requirements Development

This section details the process used to transform the set of LCS requirement published by the US Navy [US Navy 2003] into requirements suitable for use within the improved implementation. The initial US Navy requirements are found in Table H.1.

Taking this set of requirements it is possible to extract the sub-set of the requirements that can be examined at each functional group level. Figure H.1 to H.4 illustrate how the requirements from Table H.1 can be used to assess either a single sub-option belonging to a single function or a combination of sub-options from a number of functions.

Table H.1: LCS Flight 0 Requirements, from [US Navy 2003]

Category	Threshold Level	Objective Level
Total Price per Ship	Meet CAIV target in the REP	Exceed CAIV target in the REP
Hull Service Life	20 Years	30 Years
Draft at Full load Displacement	20 feet	10 feet
Sprint	1000 nautical miles at 40 Knots	1500 nautical miles at 50 Knots
Naval strike	3500 nautical miles at 22 Knots	4300 nautical miles at 24 Knots
Fleet operations	3500 nautical miles at 16 Knots	4300 nautical miles at 18 Knots
Anti-submarine warfare	500 nautical miles at 6 Knots	800 nautical miles at 8 Knots
Aviation Support	Embark and hangar: one MH-60R/S and VTUAVs, and a flight deck capable of operating, fuelling, reconfiguring, and supporting MH-60R/S/UAVsNTUAVs	Embark and hangar: one MH-60R/S and VTUAVs, and a flight deck capable of operating, fuelling, reconfiguring, and supporting MH-60R/S/UAVsNTUAVs
Aircraft Launch/Recover Sea State	Sea State 4 best heading	Sea State 5 best heading
Watercraft Launch/Recover	Sea State 3 best heading with in 45 - mins.	Sea State 4 best heading with in 15 - mins.
Mission Package Boat type	11 Meter RHIB	40 ft High Speed Boat
Time for Mission Package Change-Out to full operational capability including system OPTEST	4 days	1 days
Provisions	336 hours (14 days)	504 hours (21 days)
Underway Replenishment Modes (UNREP)	CONREP VERTREP and RAS	CONREP VERTREP and RAS
Mission Module Payload (note 3)	180 MT (105 MT mission package / 75 MT mission package fuel)	210 MT (130 MT mission package / 80 MT mission package fuel)
Core Crew Size	50 Core Crew Members	15 Core Crew Members
Crew Accommodations (both core crew and mission package detachments)	75 personnel	75 personnel
Operational Availability (Ao)	0.85	0.95

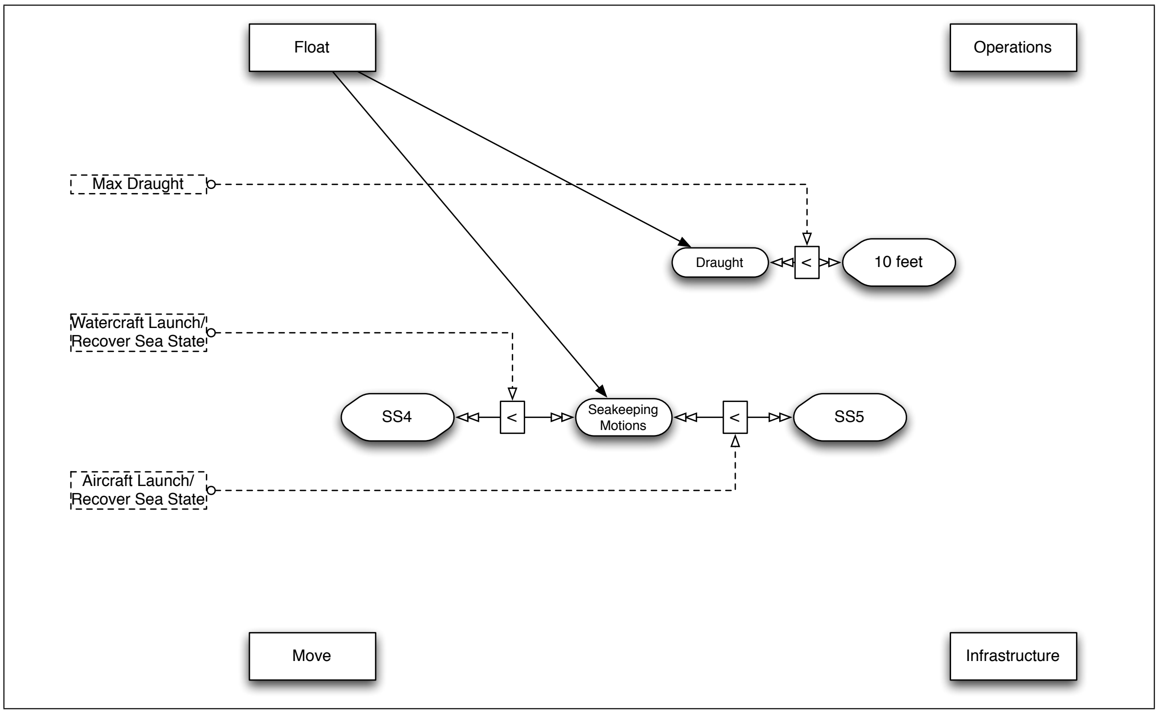


Figure H.1: Float Requirements for LCS

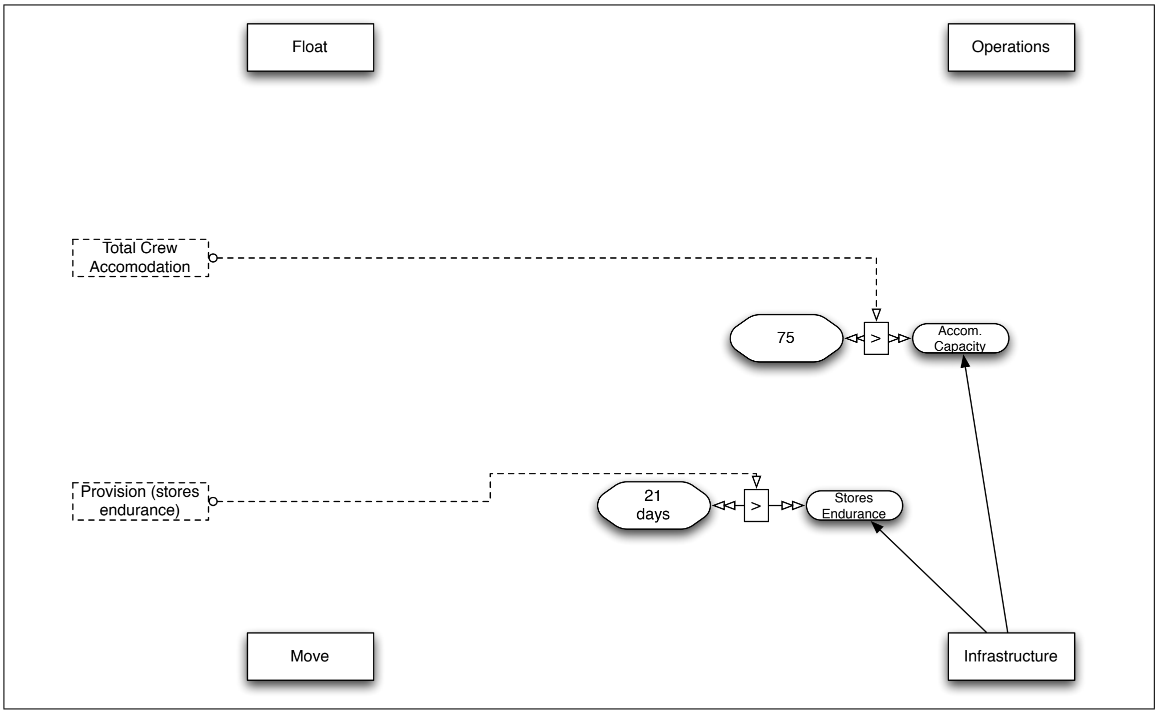


Figure H.2: Infrastructure Requirements for LCS

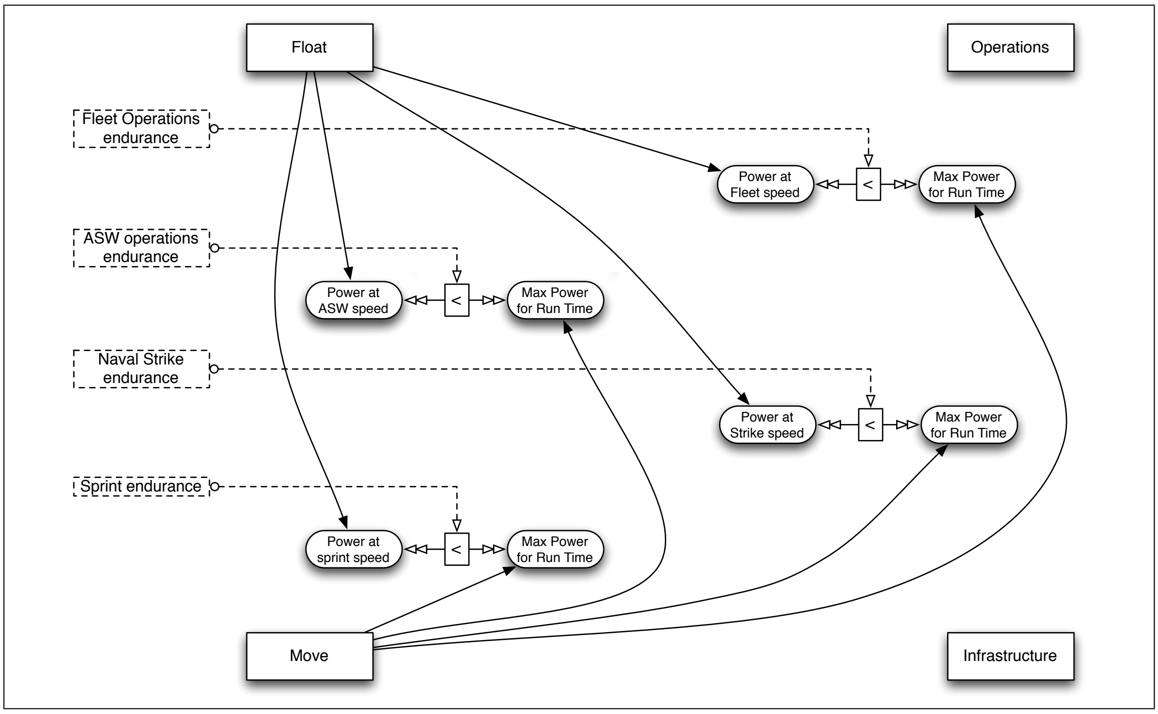


Figure H.3: Float and Move Requirements for LCS

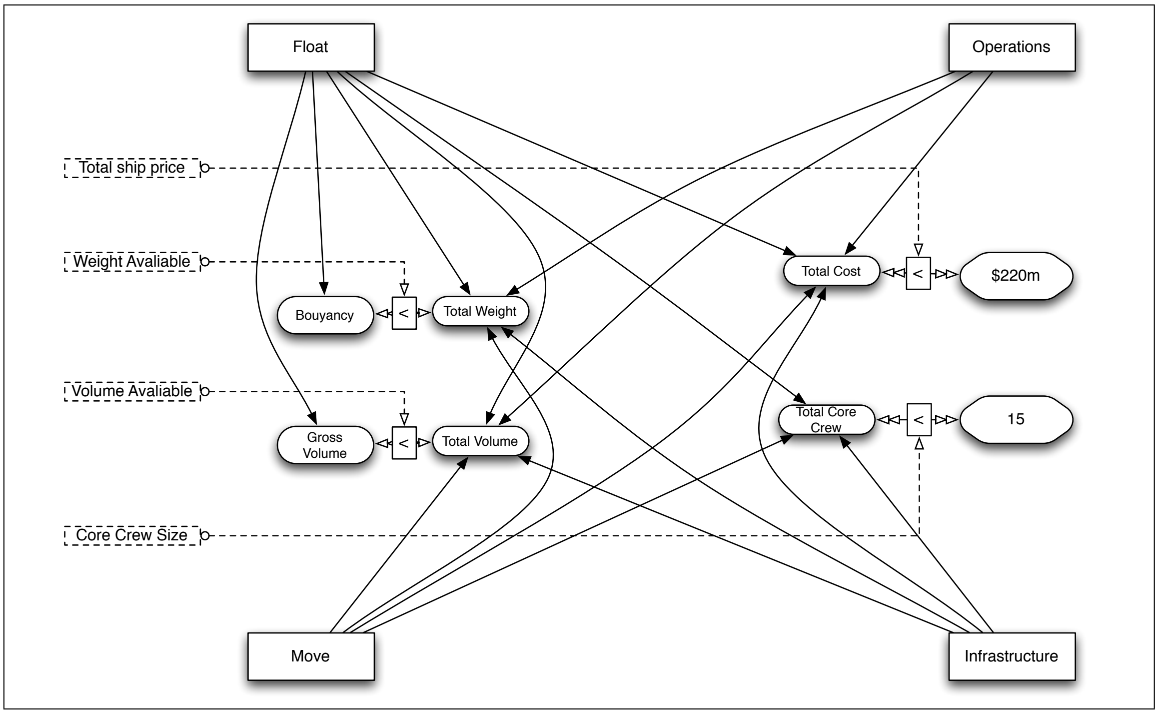


Figure H.4: Float, Move and Infrastructure Requirements for LCS

H.2 Sub-Options Generation

The following sections detail the procedure used to generate the sub-options for the Float, Move and Infrastructure functional groups.

An example of the general format of the data file used to transfer the sub-option from the tools which generates it into the library is given below:

```
createItemWithConditions value:'Name' value:Function value:Style
    value:{ {CharacteristicType1 , 1.0}, {CharacteristicType2 ,
    2.0}} value:{{ 'Condition1' , { {CharacteristicType3 , 3.0}, {
    CharacteristicType4 , 4.0}}},{ 'Condition2' , {
    CharacteristicType3 , 3.0}, { CharacteristicType4 , 4.0}}}}.
```

This file is a command instructing the library based to to create an new item called "Name", with the item's function set to "Function" and with the style of "Style". The item is assigned two characteristics of characteristic type "CharacteristicType1" and "CharacteristicType2" with the values 1.0 and 2.0 respectively. The item is assigned two conditions, labelled "Condition1" and "Condition2".

H.2.1 Float Sub-Options

For the Float sub-options the following areas were identified as being key to each Float sub-option:

- Geometry of the hullform;
- Resistance and propulsive power requirements;
- Weight and volume requirements of items within the Float functional group;
- Seakeeping performance.

Sub-options were developed for the following style of hullform: Monohull; Catamaran; and Trimaran.

The Float options have been generated using a parametric design generation tool developed specifically for this task. A number of different naval architecture tools were used in concert to develop the sub-options, these tools were:

- Paramarine, a hullform modelling and stability analysis tool [RINA 2003];
- Mitchlet, a thin ship theory resistance prediction tool [Lazauskas and Tuck 1997];
- A seakeeping tool developed at UCL [Smith 2008] and modified by the candidate.

A wrapper program was created that enabled these tools to act together. It performed the following tasks:

1. The wrapper program starts Paramarine and generates a hullform from set of basic inputs, performs stability analysis[1], then exported offsets and sectional data for use by the other tools;

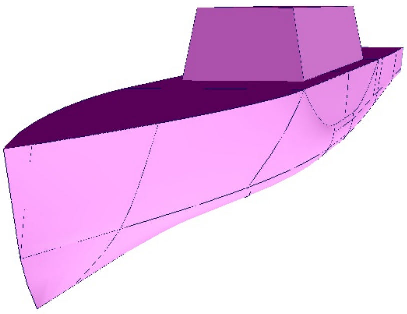
2. Offset are then imported into Mitchlet and used to perform a thin ship theory wave resistance calculation;

3. Sectional data is imported into the UCL seakeeping code and used to develop predictions for ship motions in head seas;

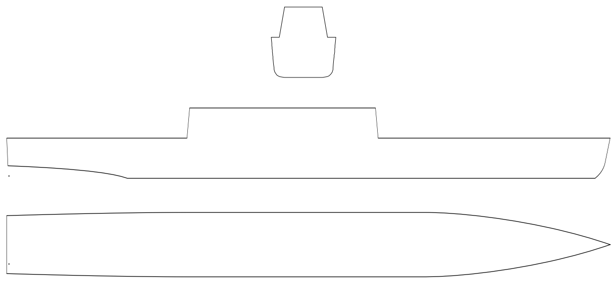
4. The data generated by all three tools is processed into a format suitable for input into the library based tool.

Both the wrapper program and files used by the different tools have been structured to allows hullforms with differing styles to be constructed quickly. An example of the output generated by this system is shown in Figure H.5, H.6 and H.7.

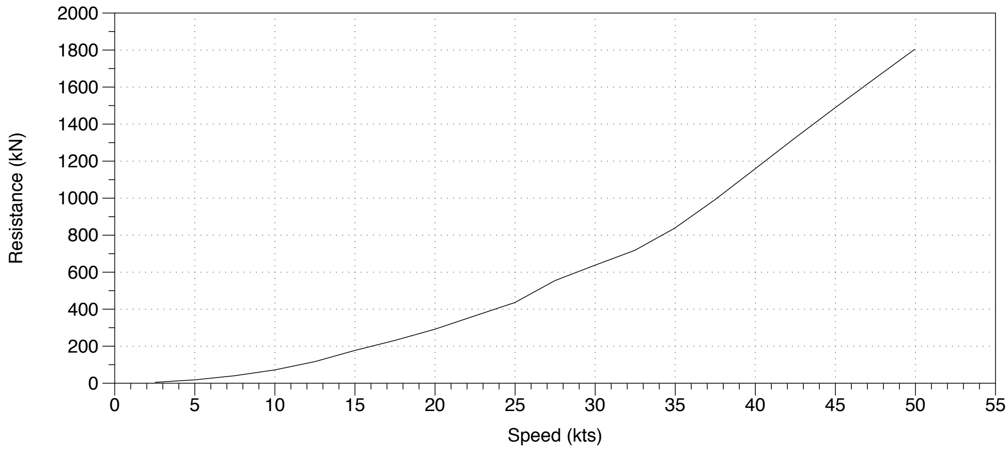
[1] For the stability analysis a range of GZ curve is found for the vessel assuming a broad range different values of KG. These curves are checked against an appropriate standard (in this case NES 109 [MoD 1999]) to determine a minimum and maximum value for KG for which the hullform passes the criteria.



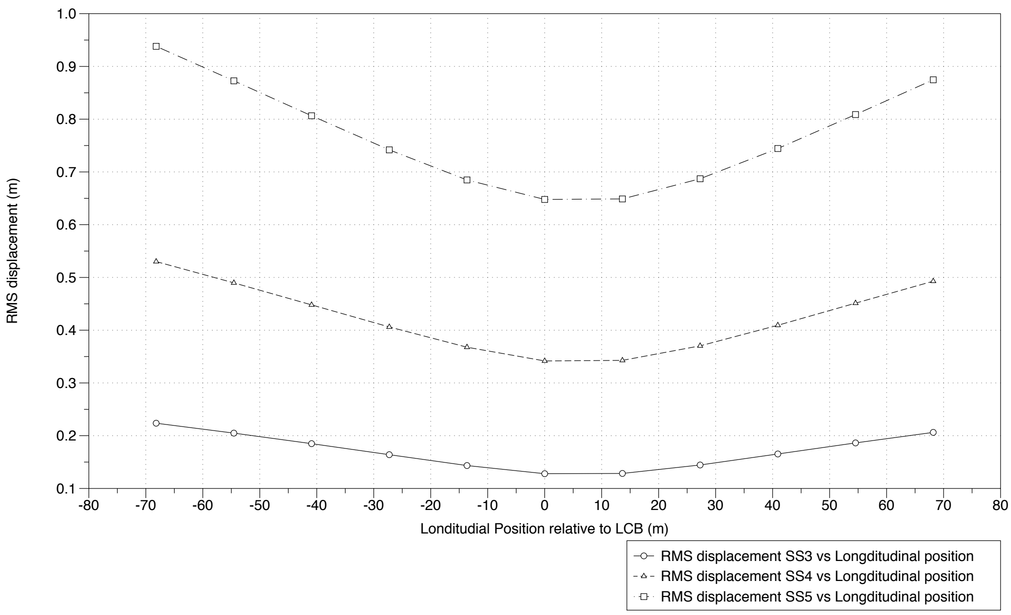
(a) Hullform



(b) Outline Body Plan

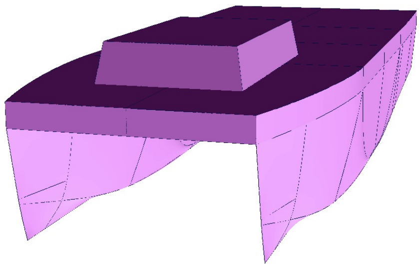


(c) Resistance

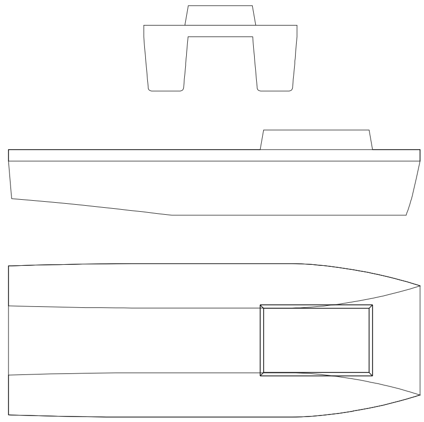


(d) Seakeeping

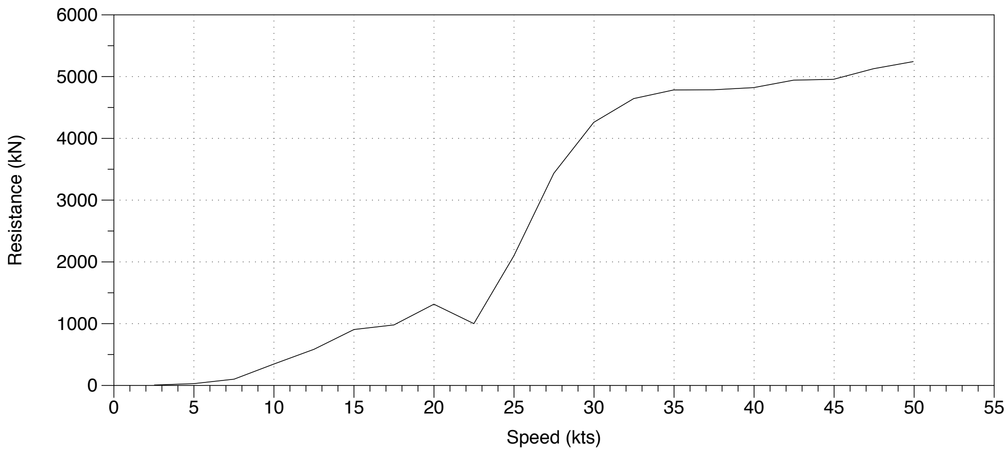
Figure H.5: Output of Float Sub-Options Generation Tool for Monohull



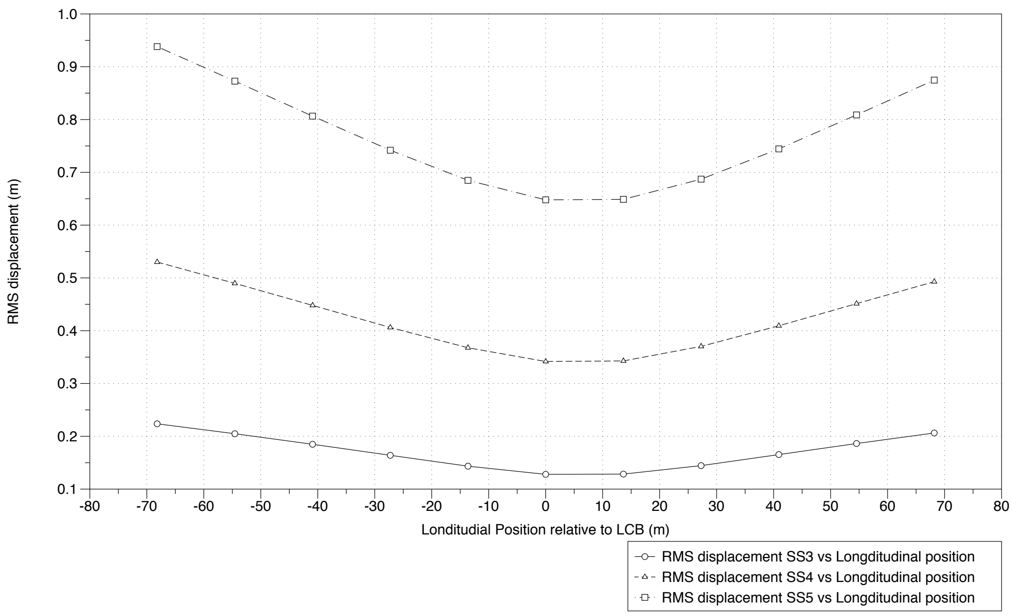
(a) Hullform



(b) Outline Body Plan

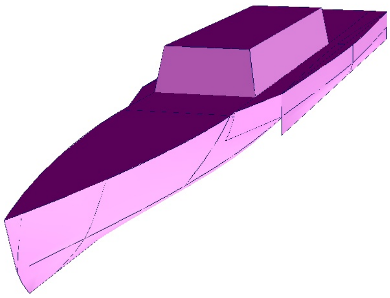


(c) Resistance

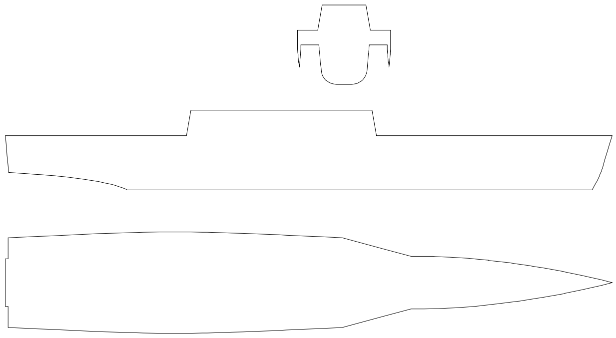


(d) Seakeeping

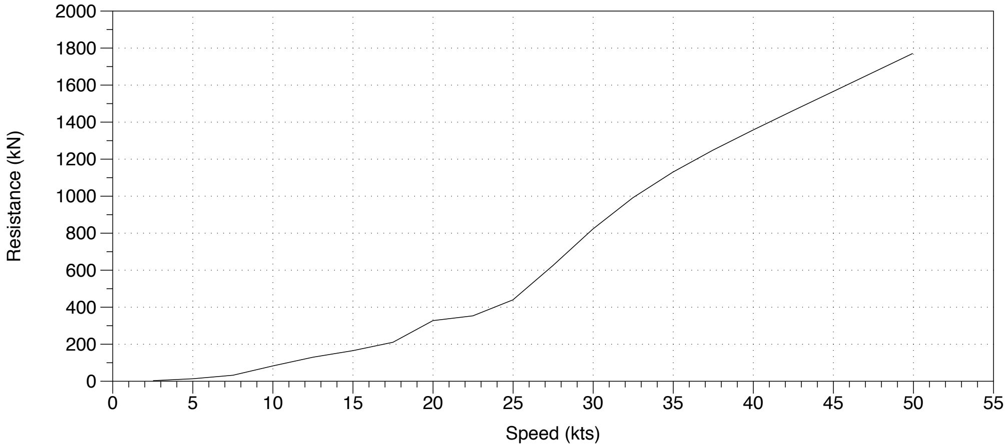
Figure H.6: Output of Float Sub-Options Generation Tool for Catamaran



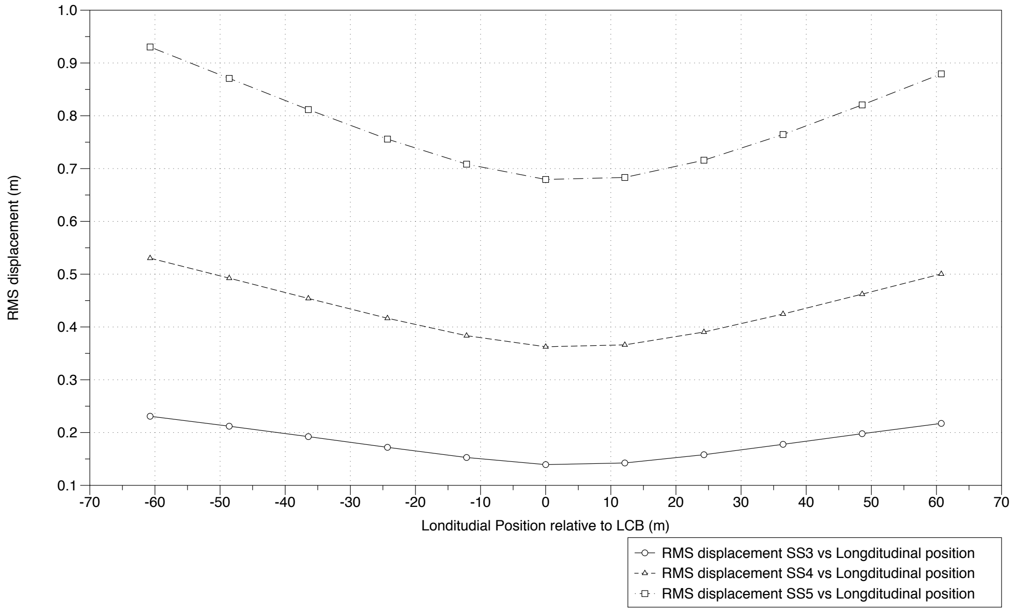
(a) Hullform



(b) Outline Body Plan



(c) Resistance



(d) Seakeeping

Figure H.7: Output of Float Sub-Options Generation Tool for Trimaran

H.2.2 Move Sub-Options

The key performance metrics of interest for the Move sub-options are given below:

- Total power range of the system;
- Fuel consumptions over the power range;
- Fuel capacity;
- Weight and volume requirements of items within the Move functional group.

Move sub-options are generated using a simple Perl[2] based program (or script) developed by the candidate that allows a large number of different machinery configurations to be produced and evaluated. This was necessary as the larger range of hullform styles would favour both different system topologies and different system components. The Perl script allows the system to be described as a number of nodes connecting sources of power (such as diesel engines or gas turbines) to power sinks (such as propellers). System performance is then explored using an optimisation routine employing the downhill simplex method in multi-dimensions [Press et al. 1986]. For a given propulsion system (with prime movers in a particular arrangement) this optimisation process found the most fuel efficient distribution of propulsor loading over the systems operating range.

An example of the output generated by this system is shown in Figure H.8. This represents a Move sub-option composed of two mirrored propulsion chains consisting of two different prime mover types connected via a reduction gearbox to a standard propeller (labelled in Figure H.8a as a 'mechanical sink'). Table H.2 and H.3 give example of the data generated using the sub-option generation tool. An example of the data file format used to transfer the sub-option from the tool used to generate the sub-option into the library is given below:

```
createItemWithConditions value:'move———FVMO—case_107—fuel_600−−2
    xWartsila12V26−2xLM2500−MechanicalSink' value:Move value:
    Mirrored__Two_PM_Types__Single_Propulsor_Type value:{{mass,
    1725.1}, {cost_mil, 132.2}, {crew, 48}, {min_X, 42.4}, {min_Y,
    4.74}, {min_Z, 5.05}, {fuel, 600}} value:{{'cond_0' , { {
    power_avaliable, 35691.8}, { fuel_con, 12.32}, { run_time, 48.6}}},
     {'cond_1' , { {power_avaliable, 32269.5}, { fuel_con, 10.69}, {
    run_time, 56.0}}}, {'cond_2' , { {power_avaliable, 27857.7}, {
    fuel_con, 9.30}, { run_time, 64.4}}}, {'cond_3' , { {
    power_avaliable, 24077.4}, { fuel_con, 8.17}, { run_time, 73.4}}},
    {'cond_4' , { {power_avaliable, 20837.0}, { fuel_con, 7.15}, {
    run_time, 83.9}}}, {'cond_5' , { {power_avaliable, 17790.9}, {
    fuel_con, 6.17}, { run_time, 97.1}}}, {'cond_6' , { {
```

[2] Perl is a high-level, general-purpose, interpreted, dynamic programming language. [Perl 2009]

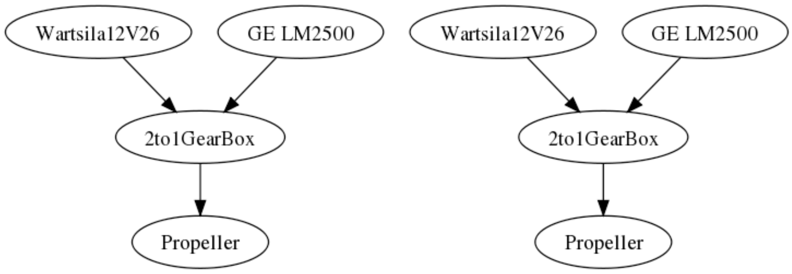
power_avaliable, 11668.1}, { fuel_con, 4.54}, { run_time, 132.0}}},
{'cond_7' , { {power_avaliable, 10834.1}, { fuel_con, 4.13}, {
run_time, 145.1}}}, {'cond_8' , { {power_avaliable, 7138.2}, {
fuel_con, 3.73}, { run_time, 160.4}}}, {'cond_9' , { {
power_avaliable, 3568.8}, { fuel_con, 1.91}, { run_time, 313.3}}}}.

Table H.2: Example Move Sub-Options Characteristics

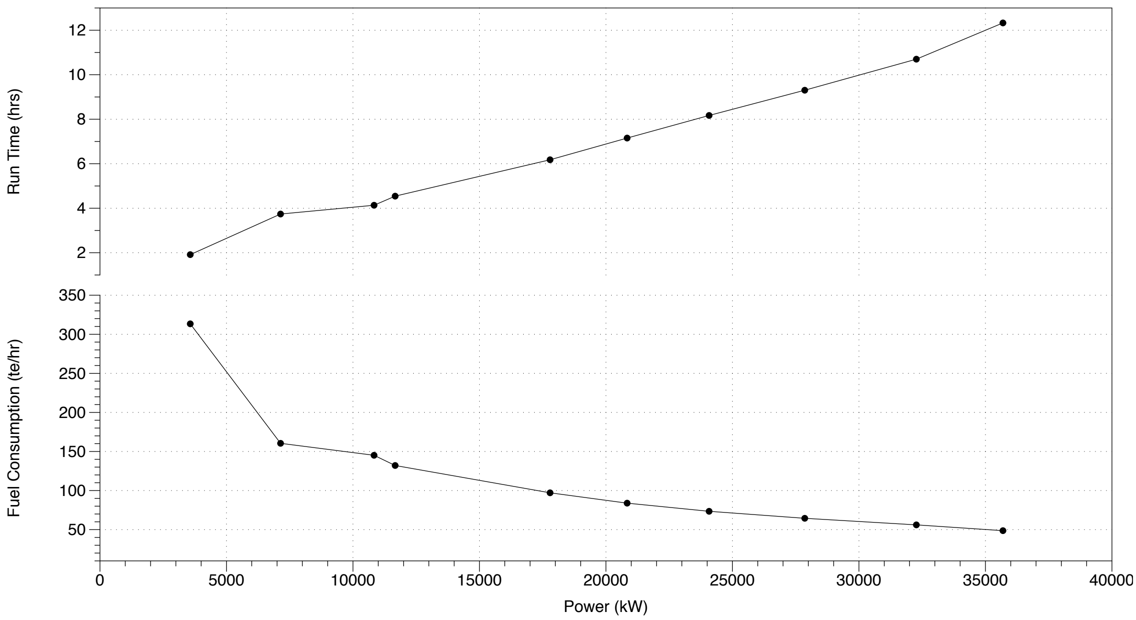
Description	Characteristic Type	Value
Total Mass [te]	mass	1725.1
Cost [£M]	cost_mil	132.2
Crew Requirement [n/a]	crew	48
Minimum Possible Length [m]	min_X	42.4
Minimum Possible Width [m]	min_Y	4.74
Minimum Possible Height [m]	min_Z	5.05
Fuel Capacity [te]	fuel	600

Table H.3: Example Move Sub-Options Conditions

Description	Characteristic Type	Value				
		'cond_0'	'cond_1'	'cond_2'	'cond_3'	…
Power [kW]	power_available	35691.8	32269.5	27857.7	24077.4	…
Fuel Consumption [te/hr]	fuel_con	12.32	10.69	9.30	8.17	…
Run Time [hr]	run_time	48.6	56.0	64.4	73.4	…



(a) System Components



(b) Power vs. Fuel Consumption and Run Time

Figure H.8: Example Output of Move Sub-Options Generation Tool

H.2.3 Infrastructure Sub-Options

The key metrics for the Infrastructure sub-options relate to the capabilities it can provide to the other sub-options and payload. The following capabilities were deemed to be important:

- Crew availability;
- Power;
- Chilled water;
- Weight and volume requirements of items within the Infrastructure functional group.

Infrastructure sub-options were generated using a parametric design tool developed by the candidate that used a simple Perl program (or script) to generate a layout for the infrastructure element of the vessel using the Paramarine ship design system. The tool allowed the development of a number of simple tree type layout that, while not optimal, provided some idea of the likely space required given certain number of crew and style of layout. By generating a number of simple layouts the system routing tools within Paramarine could be used to estimate the mass of the cabling and piping for the Infrastructure sub-options.

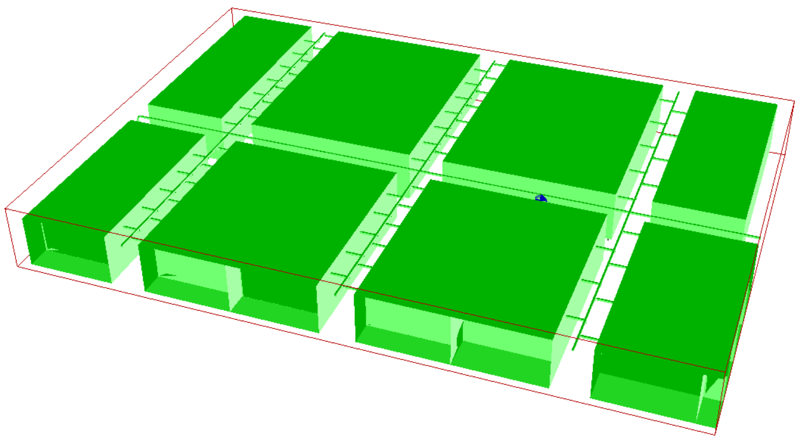


Figure H.9: Output of Infrastructure Options Generation Tool

Appendix I

Combining the Design Building Block and Library Based Approaches

This appendix was published as a conference paper entitled "Combining the Design Building Block and Library Based Approaches to improve Exploration during Initial Design" as part of the 9th International Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT), Gubbio, Italy, April 2010.

Combining the Design Building Block and Library Based Approaches to improve Exploration during Initial Design

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Abstract

University College London (UCL)'s Marine Research Group has proposed two approaches to ship concept design, the Design Building Block approach and the Library based approach. The Design Building Block approach provides an integrated model that allows the designer to explore both the configuration and numerical aspects of a design. This model allows the designer to explore innovative design solutions. In comparison, the Library based approach utilises a large library of options to provide the designer with information on acceptable alternatives given a set of requirements or constraints. This paper explore combining these two approaches to provide a tool that allows the designer to better address the import task of requirement elucidation, shaping both the customer's needs and the designer's initial solutions during the concept stage of the ship design process. The paper first introduces the Design Building Block and Library based approaches via one example showing an application of each approach. The paper then discusses the advantage arising from a combination of the approaches and shows how a combined tool could assist the designer in the initial exploratory stage of the ship design process. While the combination of these two approaches appears to be promising, further research is necessary to explore appropriate mechanisms for integration and applicability to wider design problems.

1. Introduction

The early stage of the ship design process presents the designer with an opportunity to explore radical alternatives that could satisfy the needs of the customer, the requirement owner and users. However, current design approaches and tools do not satisfy the range and depth of solution exploration in elucidating the true requirements (*Andrews 2003a*). This paper explores the potential for a synthesis between two alternative approaches, both develop at UCL.

The paper commences with a summary review of the justification for a wide exploration in the early stages of the design process by considering current preliminary ship design methods, their perceived limitations and what has been proposed as the necessary features for initial ship design methods, if they are to be comprehensive and foster a creative exploration of design options. The UCL Design Building Block approach (*Andrews and Dicks, 1997; Andrews and Pawling, 2003*) is outlined and the manner in which designs are progressed is shown to highlight the early design stages, as these benefit most from being able to assess a wide range of variants. The paper then outlines the new Library based approach (*McDonald and Andrews, 2009*) and introduces a demonstration of this approach that includes consideration of alternative vessel styles (in this case catamaran and trimaran hullforms). The latter approach allows an exploration of a wide range of solutions avoiding the limitation of many existing synthesis techniques, which cannot readily assess multiple styles concurrently. The final section of the paper considers how the Library based approach can be combined with the Design Building Block approach to open up the wider exploration of both the widest range of ship configurations and be responsive to the simulation based consideration of a wide range of aspects of design style (*Andrews and Pawling, 2006*). This includes those driven by human factors considerations, which have been previously excluded from initial ship design synthesis (*Andrews et. al., 2008*).

2. The need for a wider exploration in initial ship design

The issue in the initial design of complex ships, such as naval combatants, is that the exploration should be as wide as possible, so that all conceivable options are explored and the emergent requirements are "elucidated" from this comprehensive exploration which, importantly, informs the dialogue between the requirements owner and the concept ship designer (*Andrews, 2003a*).

While there have been numerous design approaches proposed to address the initial design phases (e.g.. the twenty six approaches to modelling the ship design process identified by the first author in *Andrews et. al. (2009)*), these approaches often fail to provide a designer with the means to rapidly explore the consequences of emergent design issues or requirements. Broad investigations of alternative options are currently undertaken, at best, by a separate investigation or exploration through distinct synthesis modelling of each alternative. In initial design this is seen to be problematic in that, either, such a comprehensive exploration is rejected, as being inefficient in the timescale this demands, or, worse, is not even addressed. This then means that the initial concept exploration is restricted, with potential solutions unconsidered, and the elucidation of the requirements is narrow, leading to downstream vulnerabilities in requirement justification and project approval processes.

Current design methods restrict the designer's ability to conduct rapid and broad explorations in the early stages of the ship design process. However, the extent of this restriction varies between methods. Some, such as the traditional numerical ship synthesis and the UCL Design Building Block (DBB) approach, are restricted by the inherent limits of human cognitive speed to consider more than one ship design type at a time. Whereas those relying on numeric selection processes (such as expert systems, neural networks and genetic algorithms, which use objectives and constraints to find a 'best' solution) are restricted by the simplistic manner in which they represent aspects where considerable human input is necessary to identify an acceptable solution (e.g. appreciation of variations in ship configuration). The first author has identified initial ship design methods as being in two categories — termed "glass and black box", respectively (*Andrews, 1994*). Thus glass box methods allow the designer to gain a detailed understanding of the driving factors in the design, highly desirable for requirement elucidation and in identifying design drivers early. However, glass box design methods are often not amenable to automation and hence cannot be used to rapidly assess a large number of options. This can curtail the designer's ability to explore a large number of solutions and to develop understanding, in contrast to finding a single 'best' solution or obtaining a high degree of insight regarding a single specific 'detailed' solution. A design method able to explore a large number of potential designs but which does not remove the designer from control over option choice is desirable.

Given the importance of the designer fully exploring potential options, as part of the concept phase of the ship design process, there remains a difficulty in that the number of options the designer can explore is always going to be limited by design imperatives (i.e. manpower, time and funds). The process of requirement elucidation, as the driving motivation in early ship design, adds a further complication. If, as a necessary part of a comprehensive early design process, the designer is also to consider different styles — with widely varying characteristics and performance — then the need to find a quicker manner to undertake a wide exploration of options becomes more challenging. Current ship design methods fail to provide a tool that adequately addresses this issue. This is due to the fundamentally solution centric approach that they adopt, typified by the following broad scheme: take inputs, develop a whole ship solution, evaluate performance, and then iterate by adjusting the inputs. This approach is not suited to the exploratory phase of the design process where designers wish to develop their understanding of the potential solution space. Furthermore, additional requirements are likely to radically change the solution space, so the wider the exploration the more robust the concept design process needs to be.

At this point it is useful to consider what features ship designers have previously requested in a concept design tool. *Betts (2000)* provides a useful checklist for potential warship design tools, while *Andrews (2003b)* considers there to be five features required to be exhibited in the outcome of any approach to preliminary ship design, if this is to meet the demands of requirement elucidation:-

1. "Believable solutions, meaning ones that are both technically balanced and descriptive;
2. Coherent solutions, meaning that the dialogue with the customer should be more than merely

a focus on numerical measures of performance and cost, and should include visual representation;
3. Open methods, in that they are responsive to the issues that matter to the customer or are capable of being elucidated from the customer or from user teams;
4. Revelatory, so likely design drivers are identified early in the design process to aid effective design exploration;
5. Creative, in that options are not closed down by the design method and tool but rather alternatives are fostered."

This can be used as a benchmark in judging whether a proposed early design approach is attractive in meeting the designer's needs. An approach able to fully support the exploratory phase of the ship design process will assist the designer in understanding the customer's needs. It should capture the impact of emerging requirements on possible solutions and not unduly constrain the designer to a limited selection of alternatives. It must be sufficiently flexible to allow the addition of new information by the designer, as it becomes available. It should aim to fulfil the above list of creative ship design system features. Finally, the method should strive to support the full range of ship design from simple batch development through to radically new configurations and technologies (*Andrews, 1998*).

3. The design approaches

3.1. The Design Building Block approach

The UCL originated Design Building Block (DBB) approach to preliminary ship design was first presented in (*Andrews and Dicks, 1997*) and outlined the consequential procedure for preliminary ship design. This was subsequently adopted in the working version of SURFCON, as part of the Graphics Research Corporation Limited (GRC) preliminary ship design tool PARAMARINE (see *Munoz and Forrest (2002)*). Further UCL design activities (*Andrews and Pawling, 2003, 2006*) spelt out the development of the practical PARAMARINE based DBB capability developed from the 1997 specification and the research demonstration presented to IMDC in 1997. The 2003 exposition was an extended application of the DBB approach, using the newly realised SURFCON implementation, to design a multi-role frigate, akin to the Royal Navy's Type 23 Frigate. The 2006 IMDC paper then described the considerable range of ship design studies that had been undertaken by the UCL DRC in the intervening three years, demonstrating the utility of the PARAMARINE implementation of the DBB approach.

The distinguishing feature of the Design Building Block approach, outlined in a 1998 Royal Society paper (*Andrews, 1998*) and summarised in Figure 1, is its use of an information rich interactive graphical interface, coupled with a flexible configurational model of the ship and integrated with comprehensive numerical analysis of the main naval architectural issues to achieve initial design balance. The incorporation of a flexible configurational model, from the earliest stages of the design process, allows the early design description to reflect a wide range of customer and user requirements, including through life costing, human factors, health and safety issues, environmental issues, supportability, sustainability, reliability and adaptability and ship survivability.

A further fundamental feature of the Design Building Block approach is the use of a functional breakdown of the design. This Functional Hierarchy is used through the SUBCON designs based on a top level description using four functional groups: FLOAT; MOVE;, FIGHT (Service, Payload or OPERATIONS in a merchant vessel); and INFRASTRUCTURE. This breakdown system is used instead of historical skill and task based systems, such as the UK MoD NES 163 (*MoD 1989*) to encourage innovative solutions, by removing the conservative assumptions of traditional systems and structures implied by the previous weight breakdown hierarchy, although a translation can be made back to exploit historic data for aspects, such as costing.

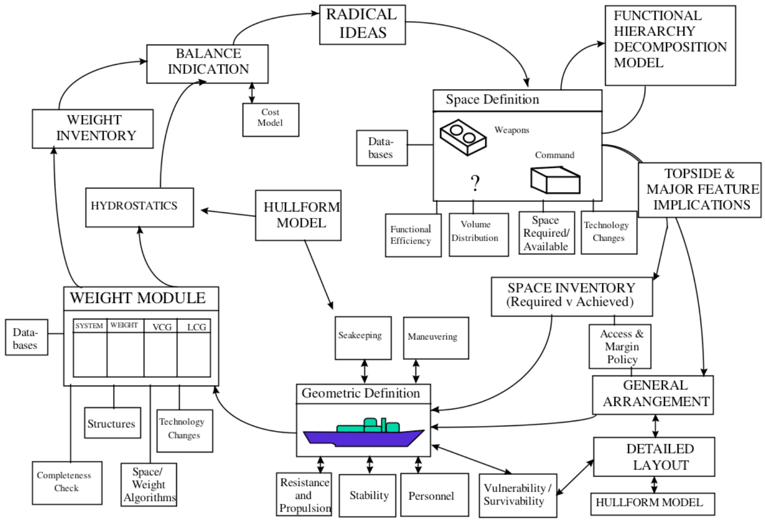


Fig.1: The Design Building Block approach applied to surface ship design synthesis (*Andrews and Dicks, 1997*)

3.1.1. A process for employing the Design Building Block approach

A description of a process for utilising the Design Building Block approach in the preliminary design of ships is presented in (*Pawling, 2007*). This is derived from a variety of design studies conducted at UCL (*Andrews, 1986; Dicks, 1999; Pawling, 2001*). These studies extended across both a variety of ship roles and a wide range of hullforms (e.g. monohull, trimaran, SWATH). While the detail procedures used in each of the studies varied, given the nature of the design model and objectives for each of the studies were different, this meant that a common detailed procedure was found to be impractical. However, it was possible produce a generic illustrative sequence for progression of a design using the DBB approach and this is shown in Figure 2.

The early variants developed in the Major Features Design Stage (MFDS) represent significantly different overall layout configurations, which are not developed to a high level of detail and are, therefore, akin to rough sketches. One of these layouts is then taken forward to the Super Building Block Design Stage (SBBDS). However, as shown by the dotted arrows, it is also possible to develop several variants to a higher level of detail, (some UCL design studies have demonstrated this approach (*Andrews and Pawling, 2004*)). Given that the process of design is iterative, feedback mechanisms exist not only within the processes of comparison and selection, but also between the stages of design development, allowing information to be fed back into an earlier stage, as shown in Figure 2.

Pawling (*2007*) also highlights the perceived advantages that arise from integrating numerical models and methods able to explore a set of options. These tools could be employed to reveal the nature of the possible solution space, for each of the major options or variants. This would allow assessment of the design topology selected and reduce the pre-determination of the design form, identified as a potential problem with the application of the Design Building Block approach (*Dicks* [1999]). For example, if a large set of options were to be produced, for each variant the designer develops, then feedback could be improved. The DBB approach could be of great assistance in this respect, due to the enhanced understanding of the design provided by the interactive graphical display. This could then lead to a common environment for improved communication between all parties involved in the design evaluation process.

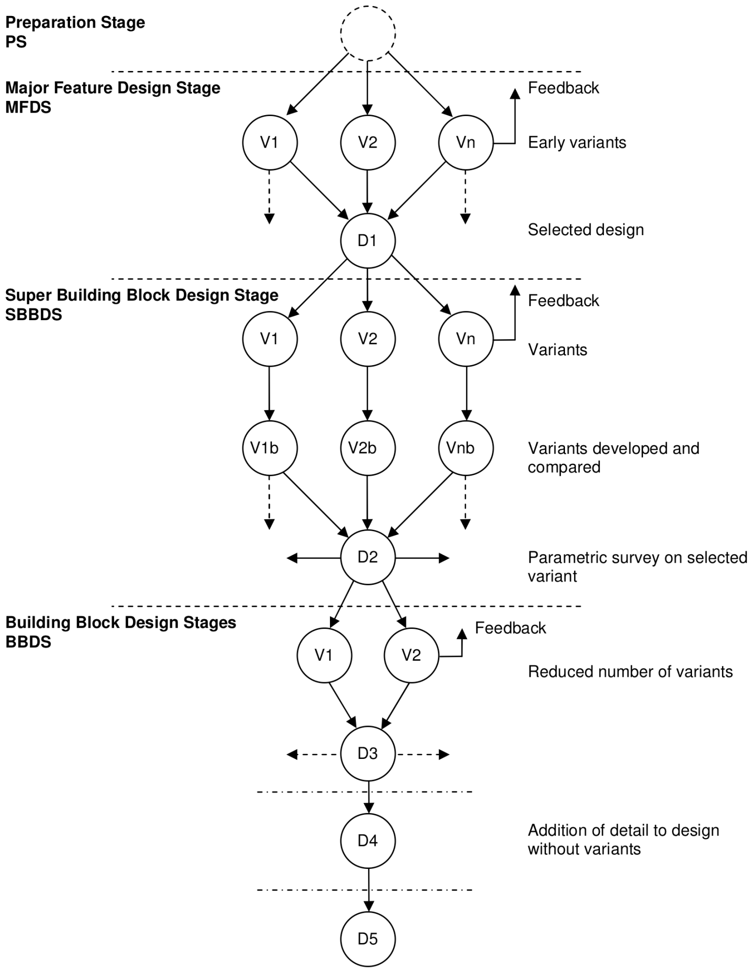


Fig.2: Illustrative diagram showing the progress of a design using the Design Building Block approach (*Pawling, 2007*)

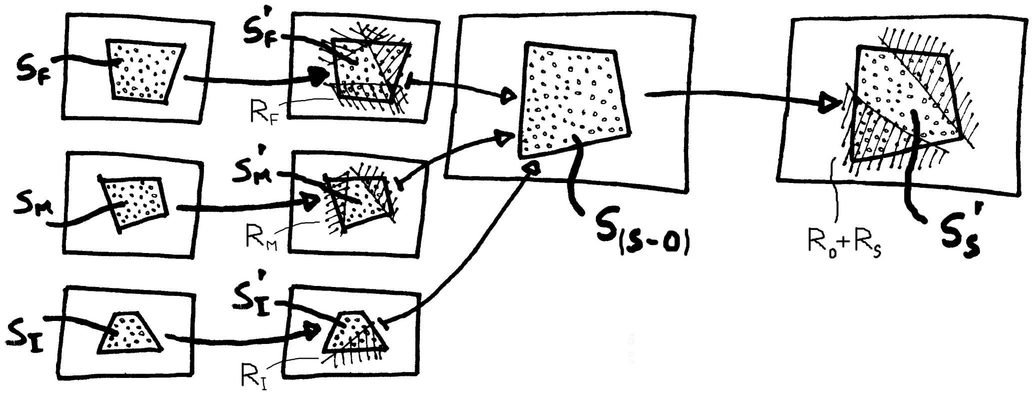
3.2 The Library based ship concept design approach

McDonald and Andrews (2009) presented the UCL Library Based approach to initial ship design. In essence this approach is based upon a limited library of possible options describing a large number of ship designs, which the designer can rapidly filter to find options that satisfy the current design requirements. The initial library must be broad enough to contain an array of options that will be of interest to the designer. To prevent the number of options within the library growing to an unmanageable size, a process of decomposition and down selection is applied to reduce the number of options that must be stored within the library. If a ship option is decomposed into a number of sub-options then these can be stored in place of whole ship options. The Library based approach decomposes options into the same functional categories as used by the DBB approach: Float; Move; Fight (in the case of a naval combatant) or Operations (in the case of a commercial ship with a cargo or service function); and, Infrastructure. The sub-options have then to be combined to produce a larger set of possible whole ship options, which have been termed ‘combined options’ (*McDonald and Andrews, 2009*).

The options from the library could be filtered via a number of different search mechanisms, such as those employed within database tools (*Atzeni et. al., 1999*). The power and speed of current search techniques should be familiar to any user of Internet search engines. By assessing the options pre-calculated characteristics and performance a rapid down selection process can be easily implemented.

Furthermore, if part of this down selection process occurs at a sub-option level, by making use of an appropriate subset of the requirements, this will significantly reduce the number of combined options that need to be considered. The possible combinations of remaining sub-options could then be used to produce a set of combined options. Finally, the set of combined options, which meet the overall constraints and requirements, can be found.

Figure 3 summarises the library based approach. At the left of Figure 3(a) are the sub-options for the three functional groups ($\mathbf{S_F}$, $\mathbf{S_M}$, $\mathbf{S_I}$) that are stored within the library. These sub-options are then assessed against appropriate subsets of the ship requirements (R_F for the Float options, R_M for the Move options and R_I for the Infrastructure options), with those that fail to meet given thresholds of performance being removed from consideration. The subsets of the requirements will differ between the functional groups (e.g. Float sub-option removed by requirements such as upper deck length to accommodate the combat system equipment). Such a weeding out process would then result in three sets of acceptable sub-options $\mathbf{S'_F}$, $\mathbf{S'_M}$, $\mathbf{S'_I}$ (Figure 3(b)). A suitable mapping (*McDonald and Andrews, 2009*) allows the three sets of sub-options to be combined into a new set of combined ship options that initially exclude the demands of the operational items, $\mathbf{S_{(S-O)}}$ (Figure 3(c)). The remaining requirements can then be used to delete the unacceptable options from the set of combined ship options excluding the $\mathbf{S_{(S-O)}}$ demands. This would include both those requirements originating from the demands of the Operations functional group R_O (e.g. available internal volume for 'payload') and those ship requirements R_S that encompass other customer needs and span several functional groups (e.g. maximum speed requirement). To assess some of these requirements performance prediction methods may need to be employed to predict values not stored within the Library or account for major interactions between sub-options. These values could be found using a fast calculating method (*Maroju et al, 2007*). This will result in the final set of acceptable combined ship options that can accommodate the payload $\mathbf{S'_S}$ (Figure 3(d)). This collection of options would then be presented to the designer.



(a) (b) (c) (d)

Fig.3: Iconic Representation of Option Exploration Process Based on a Set of Functional Ship Sub-Options (*McDonald and Andrews, 2009*)

3.2.1. Presentation of Library based Synthesis

This section briefly outlines a demonstration of the library based ship concept design approach. This employs a database backed object-oriented programming approach to rapidly explore options representing a range of alternatives stored in a library by using a set of requirements selected from a recent actual naval ship design programme.

Adopting a database storage system enables the down selection process to make use of the database's rapid search and query capabilities. Items returned by the database can then be realised as instances of objects within the implementation. This specific implementation is built using a number of different objects that act together to create a data model able to perform the key tasks, which underlie the approach as outlined in the previous sub-section. The seven primary types of objects that make up the improved implementation are:

- Items;
- Characteristics;
- Values;
- Conditions;
- Functions;
- Styles;
- Characteristic Types.

These seven object types are illustrated in Figure 4. This shows each object's attributes (the variables stored within the object) and the relationships the object has to other objects in the Library. A line terminating with two single arrows denotes a one–to–one relationship. A line terminating in one single arrow and one double arrow denotes a one–to–many relationship. Finally, a line terminating in two double arrows denotes a many–to–many relationship. For example, an Item object may contain relationships linking it to a number of Characteristic objects while each Characteristic object can only be related to a single Item object, this relationship can be defined as a one–to–many relationship. This description of the objects with relationships allows the objects within the Library to be mapped to a relational database structure, which allows storage and rapid retrieval, for a given set of constraints.

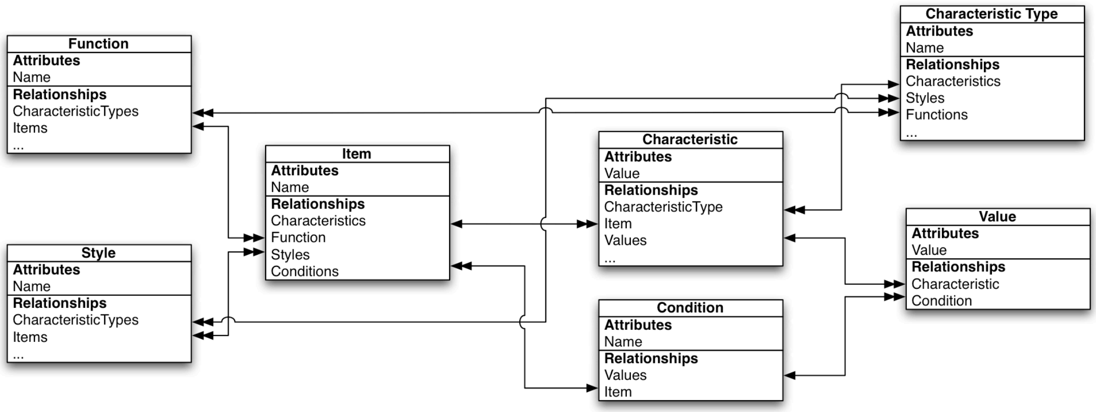


Fig.4: Key Objects within the Library

The process of searching the Library for appropriate options and combining these to form new options, which are then presented to the designer, is performed by a number of actions. Actions are split into two types: Fetch Actions that retrieve Item objects from the library and Combine Actions that generate new options by combining sub-options belonging to a number of input actions. These two types can be combined into a hierarchical tree of Actions with Combine Actions as branches and Fetch Actions as leaves, as shown in Figure 5. This differs from the iconic representation, shown in Figure 3 as a two stage combination process, is employed to develop combined Float-Move options and then combined Float-Move-Infrastructure options.

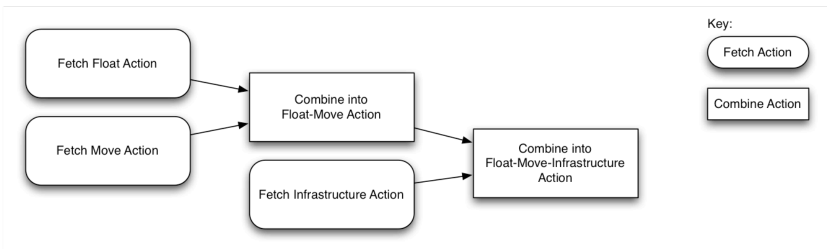


Fig.5: Example Hierarchical Tree of Fetch and Combine Actions for the Improved Implementation of the Library Method

3.2.2. An example method demonstrating the Library based approach

Before the Library based approach can be used to explore a set of options the library must be populated with data. In this case Float, Move and Infrastructure sub-options were developed then stored in the library. The tools used to synthesise the sub-options will not be described in detail here, however a brief description of aspects, identified as being key to each Float sub-option, is provided below showing the data incorporated into each sub-option:

- Generation of the hullform geometry;
- Resistance and propulsive power requirements;
- Weight and volume estimation of items within the Float functional group;
- Intact stability analysis for large angles against appropriate standards;
- Seakeeping performance in head seas.

Sub-options were developed for monohull, catamaran and trimaran hullform styles, with representative image shown in Figure 6. Using this tool 3787 sub-options were developed, comprising 1458 monohull, 1080 catamaran and 1249 trimaran sub-options, respectively. All 3787 Float sub-options are plotted in Figure 7 to demonstrate the wide range of solutions that were generated.

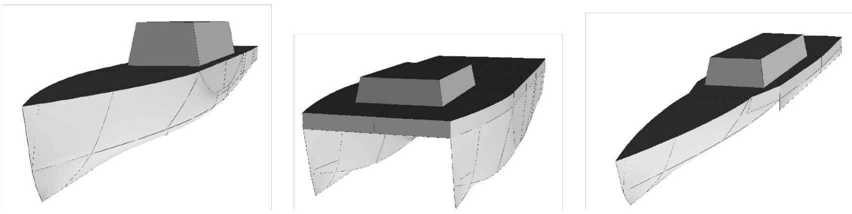


Fig.6: The Three Styles Explored for the Float Sub-Options

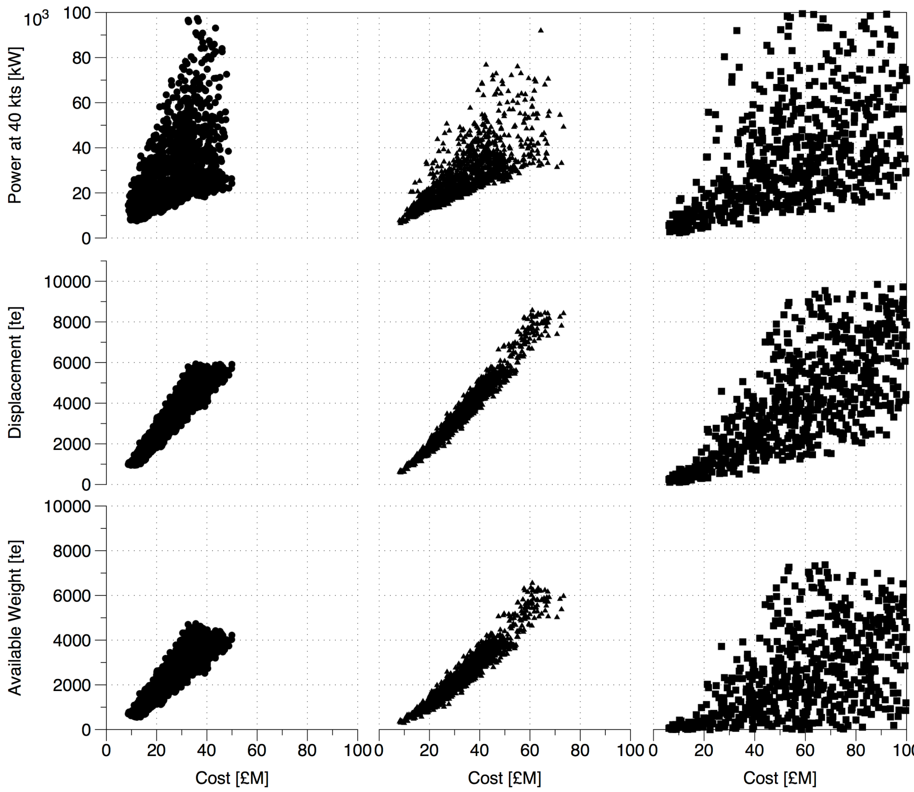


Fig.7: Maximum Length vs. Total Displacement for All Float Sub-Options in the three example Hullform Styles

Table I: Extract from the Set of Functions and Requirements from LCS Programme (*US Navy, 2003*)

Function	Threshold Requirement		
Float	Draught	<	6.10 meters
Infrastructure	Max Accommodation	<	75
Combined Float–Move	Range	>	1000 nautical miles at 40 Knots
Combined Float–Move	Range	>	3500 nautical miles at 22 Knots
Combined Float–Move	Maximum Speed	≥	40 Knots
Combined Float–Move–Infrastructure	Crew available	≥	Crew demand
Combined Float–Move–Infrastructure	Total cost (excluding payload)	≤	£66M

The design study that occurred as part of the US Navy's LCS programme (*Long and Johnson, 2003*) was seen to provide a suitable test case. The set of requirements in Table I are based upon those defined at the start of the US Navy LCS design competition. Several of these requirements were not explicitly defined in the original LCS requirement (*US Navy, 2003*). Using the threshold requirements defined in Table I the following down selection and combination Actions were implemented (more extensive details of these steps is provided in (*McDonald and Andrews, 2010*):

- **Action A - Float Sub-Options Down Selection:** The initial library contained 3787 Float sub-options. Requirements were applied to down select these sub-options until 2964 Float sub-options remained.

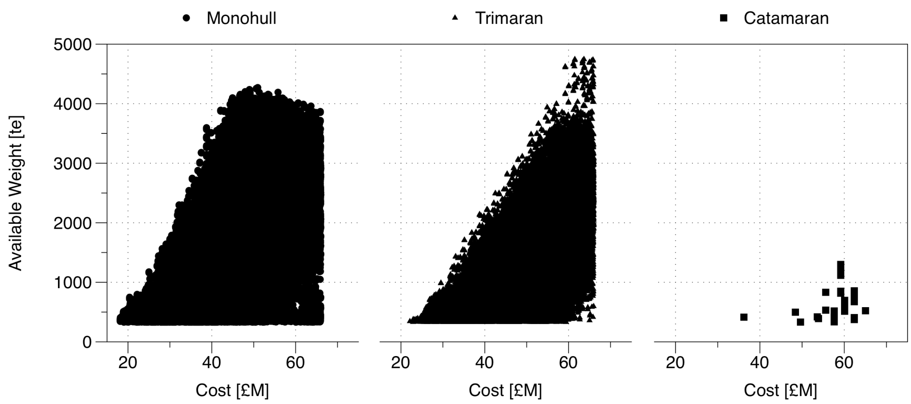
- **Action B - Move Sub-Options Down Selection:** As with Action A the 2560 Move sub-options stored in the Library were down selected to 585 acceptable Move sub-options;

- **Action C – Infrastructure Sub-Options Down Selection:** As with Actions A and B the 583 Infrastructure sub-options stored in the Library were down selected to 205 acceptable Infrastructure sub-options;

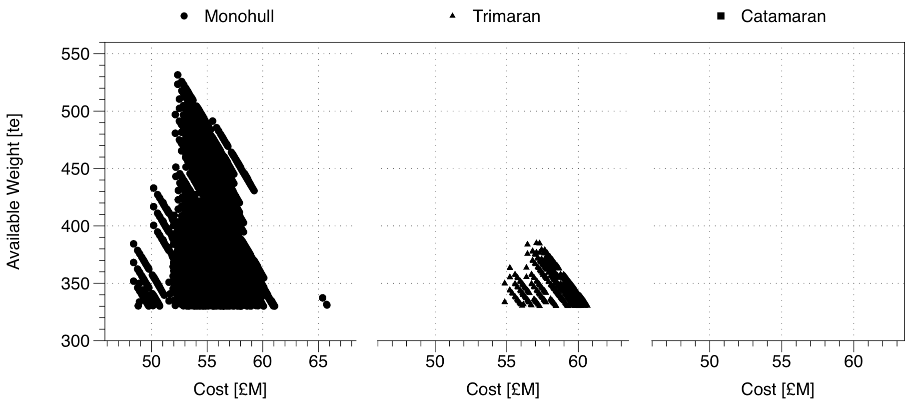
- **Action D - Float–Move Options Combination and Down Selection:** Combining the 2964 remaining Float sub-options and 585 remaining Move sub-options gives a possible 1,733,940 combined Float-Move options. However, both incompatibilities between the functional groups and design generated requirements were used to down select these combined options. In this case 51,450 possible combined options were rejected due to incompatibilities between the functional groups (i.e. the Move sub-option was unsuitable for the Float sub-option). The remaining possible combined options were then assessed using the requirements to down select acceptable options. This down selection resulted in 136,749 combined Float-Move options remaining.

- **Action E - Float–Move–Infrastructure Options Combination and Down Selection:** Combining the 119,837 combined Float-Move options, from the previous step, with 205 Infrastructure sub-options gave 24,566,585 possible combined Float-Move-Infrastructure options. Once again requirements were used to down select these new combined options. This down selection resulted in 25,195 combined Float-Move-Infrastructure options remaining.

Figure 8a shows the procurement cost vs. available weight for Combat Systems for Remaining Combined Float-Move Options, at conclusion of Actions D. This figure shows the remaining Float options separated into three plots by the options hullform styles. While a large number of combined Float-Move options of the trimaran and monohull styles are able to satisfy the requirements imposed up to this stage, a far smaller number of combined options with a catamaran hullform are acceptable. The results of Action E, the final combination and down selection, is shown in Figures 8b. At this point these remaining 25,195 acceptable combined Float-Move-Infrastructure options fully satisfy the set of requirements that have been applied. The grouping of acceptable options is plotted in terms of the weight available for the combat system and the ship solution procurement cost, namely without the combat system equipment cost. Figure 9 presents, as histograms, the number of options that remain. From these plots it can clearly be seen that no Catamaran style solutions remain but that either a monohull or trimaran style option may provide an acceptable solution for the specified requirements.



a) Remaining Combined Float-Move Options, at Conclusion of Action D



b) Remaining Float-Move-Infrastructure Options, at Conclusion of Action E

Fig.8: Available Weight vs. Procurement Cost for All Float Sub-Options in the three example Hullform Styles

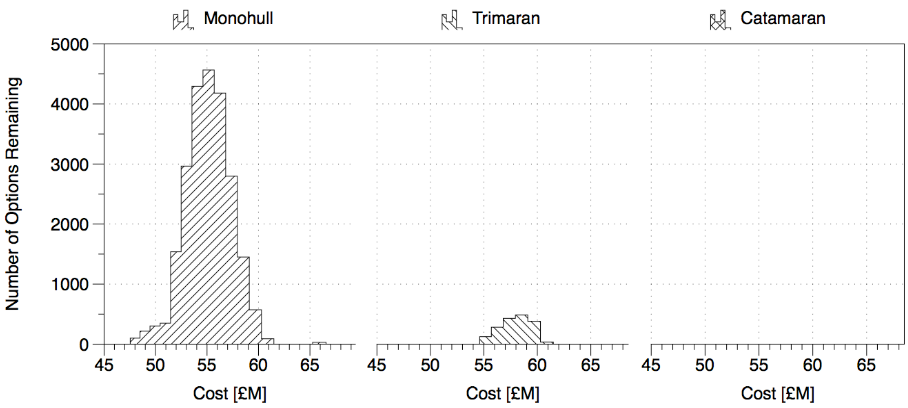
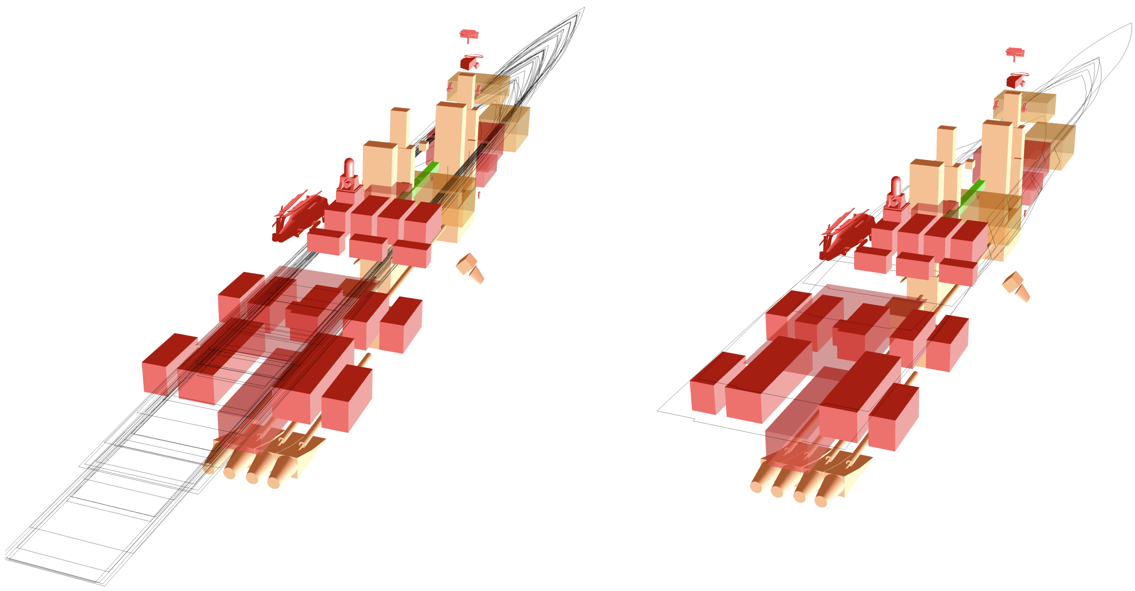


Fig.9: Number of Combined Float-Move-Infrastructure Options Remaining for Varying Procurement Costs, at Conclusion of Action E, showing Three Hullform Styles

4. Combining the Design Building Block and Library based approaches

As stated previously, the aim of the Library based tool is to provide the designer with information on the range of options that are available to the designer. Figure 10 shows how the outputs of a Library based ship design tool could be used to better inform a designer by being combined with the Design Building Block (DBB) approach, to indicate to the designer how the Library options relate to the architectural configuration of the component spaces in the ship. The vessel chosen is the LCS derived DBB design whose detailed concept evolution is outlined by *Andrews and Pawling (2009).* In this case a number of outlines have been indicated illustrating the gross geometry of the remaining Library derived options (i.e. those generated by the library based tool, which have not been removed by the requirements input by the designer). As the designer begins to define and develop the design (in this case using the configuration driven tool) additional constraints will emerge — e.g. positioning payload along an upper deck may define a minimum length or machinery layout may drive beam at certain longitudinal locations. These new constraints can be used to further refine those remaining options that 'make physical sense'.

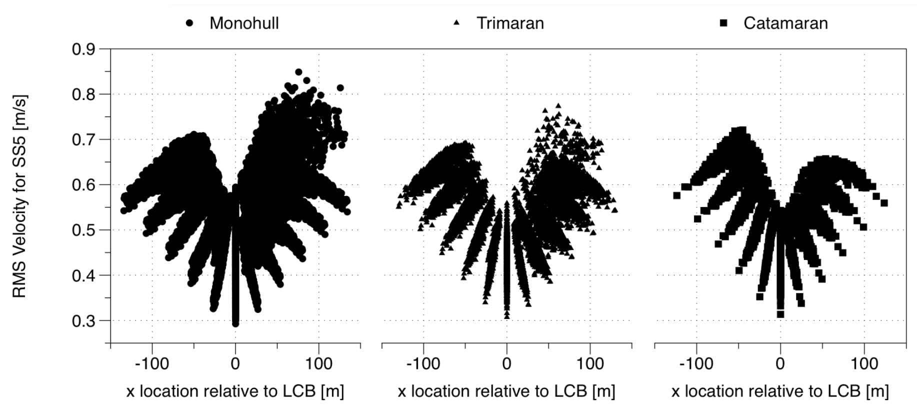


a) Monohull b) Trimaran

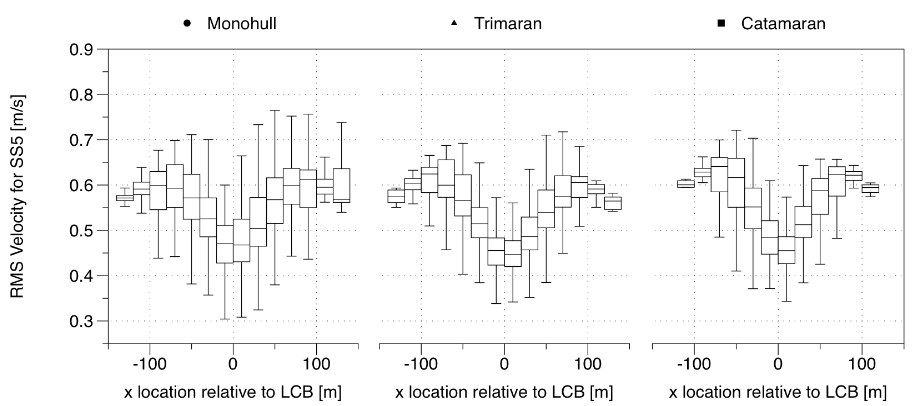
Fig.10: Illustrative Example of Integration with Design Building Block Approach

One substantial benefit of the library based approach is the rich variety of design data which it is able to store. For example, the current implementation stores sub-option information, such as ship motions and power-speed data, that can allow the designer to gain insights into the ship performance for a range of sub-options. As this data is pre-generated the designer is able to rapidly access information normally not likely to be available until later in the design process, when a more detailed ship definition can be analysed. This has the potential to help guide the designers as they explore options at the outset of the design process.

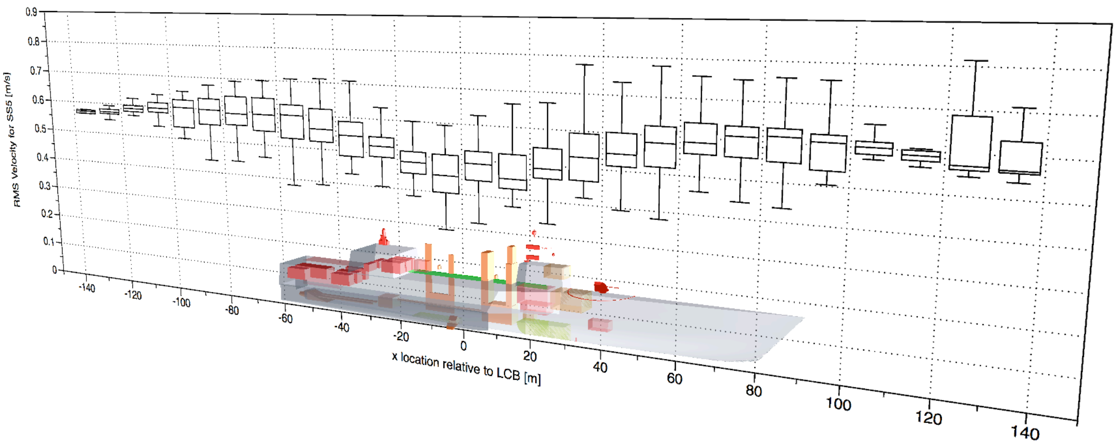
Alternatively, useful information could be extracted from other performance metrics within the library and used to guide the ship's layout. For example, by examining the options or sub-options obtained using the Library based approach, an earlier assessment of performance measures should be possible, rather than the normal approach in which investigations are undertaken after a detailed design has been developed. Figure 11 shows how this information could be displayed to help guide the designer in positioning systems with motions limitations (such as those required for helicopter operations). In this case the magnitude of vertical motions (Root-Mean-Squared (RMS) velocity in Sea State 5 (SS5)), relative to the distance from the hullform's longitudinal centre of buoyancy (LCB), is used to identify locations that are unacceptable. Two alternative presentation formats are shown in Figure 11. Figure 11a shows the data points from the library, while Figure 11b shows how processing this data, using a number of box plots, can provide improved guidance on the likely performance of the remaining options in the library. Finally, Figure 11c shows the potential of incorporating this information in conjunction with a Design Building Block model of a remaining option.



a) Point data for Float sub-options



b) Box plot of Float Sub-options



c) Box plot for Monohull hullform options within Paramarine

Fig.11: RMS Velocity vs Distance from Longitudinal Centre of Buoyancy (LCB) for a specific Float sub-option

5. Discussion

Referring back to *Andrews'* (*2003b*) list of features, necessary in a approach able to fully support the initial ship design process, allows an assessment of the utility of the Design Building Block approach combined with a Library based approach against the generic needs of preliminary ship design. The following responses are considered appropriate for the combined approach outlined in this paper:

1. Believable solutions: the options proposed by this approach satisfy a set of constraints defined by the designer. These constraints can be used to ensure that the developed solutions are technically balanced and the combine/discard mechanism eliminates unreasonable options;
2. Coherent solutions: Integrating the method presented here with an architectural model (as shown in Figure 10 & Figure 11c) allows a dialogue with the customer beyond simple numerical measures of performance and cost. The combined Library and DBB approach allows the designer to present the customer with an integrated configuration based design, but at the same time allows the rapid exploration of options using the library;
3. Open methods: The rapid manner in which the options are down selected is highly amenable to alteration, thus allowing the designer to respond quickly to issues raised by the customer/requirements owner. Coupling this method with an appropriate configurational and numeric design tool should allow rapid exploration of options, improving the design team's responsiveness to queries and hence communication with the customer/requirements owner;
4. Revelatory: The proposed method can be used to quickly identify numerical design drivers early in the design process. But to realise its full potential as an aid to effective design exploration, links to the DBB approach, as outlined above, need to be more fully realised;
5. Creative: Compared to other ship design methods, by allowing the designer to postpone the selection of style, this approach allows options to remain open until later in the design process, fostering the development of hullform style alternatives that usually are ignored due to the difficulty in assessing them alongside conventional (monohull) options.

The concept of linking the Library and DBB approaches to ship design raises several issues for future investigation in developing both a broad approach and a more detailed procedure for use in design:

- Should the Library based approach be used to define limits on the layout, or should a partial layout be used as a selection tool in the Library based approach? Both methods have potential application in the exploration of (and importantly, generation of) design options and variants as shown in Figure 2. This also raises the issue of the degree of automation or parameterisation of ship design models that would be acceptable in the combined approach.
- Can the Library based approach be used as part of an iterative design process? Considering the partial layout shown in Figure 10, new constraints could be created (or old ones modified) that imply a re-iteration of the Library selection process would be appropriate. Given the Library based approach is applicable over a wider range of problems than hullform selection (such as addressing certain aspects of internal arrangement), then the incorporation of emergent drivers and relationships in an iterative process would be important.
- How can graphical user interfaces be used to improve the effectiveness of designer investigation and understanding of the solution space. With the incorporation of layout aspects, the design is no longer being compared against a simple performance metric, so research is needed into methods that make use of all aspects of 3D environment, to allow the designer to extract valuable information from the selected options.

6. Conclusions

This research has explored the potential utility of combining two alternative design methods, namely the DBB approach and the Library base approach. By combining these, an integrated approach has been developed able to rapidly tackle the requirement elucidation need for wide exploration of options, while retaining the DBB approach's key feature of allowing the designer to explore innovative configurational alternatives. This combination can provide a basis better able to assist the designer in addressing the problem of requirement elucidation.

The combined DBB and Library based approach outlined is considered to provide a first step towards a tool that could satisfy Betts' and Andrews' lists of features supporting the very early stages of the ship concept design process. However, further work is seen as necessary for it to be incorporated in the preliminary ship design process for real naval ships:

- Demonstration of the application of the tool to a problem with a wider range of styles (for the hullform, machinery and configuration) and differing ship roles. This would ultimately require a range of comparable designs to be developed;
- Exploration of alternative methods of presenting the designer with information on the hullform styles suggested by the Library based approach in the context of a configuration based design environment (i.e. the DBB approach);
- Testing of the combined approach against actual designs produced by conventional methods.

References

ANDREWS, D J, (1986), *An Integrated Approach to Ship Synthesis*, Trans. RINA, Vol.128, London: RINA

ANDREWS, D J. (1994) *Preliminary Warship Design*. RINA Transactions, volume 136:pp. 37–55.

ANDREWS, D J. (1998) *A Comprehensive Methodology for the Design of Ships (and Other Complex Systems)*. Proceedings of the Royal Society A, volume 454:pp. 187–211.

ANDREWS, D J. (2003a) *Marine Design - Requirement Elucidation rather than Requirement Engineering*. Eighth International Marine Design Conference (IMDC'03).

ANDREWS, D J. (2003b) *A Creative Approach to Ship Architecture*. RINA International Journal of Maritime Engineering, volume 142, September 2003.

ANDREWS, D J; DICKS, C. (1997) *The Building Block Design Methodology Applied to Advanced Naval Ship Design*. Sixth International Marine Design Conference (IMDC'97).

ANDREWS, D J; PAWLING, R G, (2003), *SURFCON - A 21st Century Ship Design Tool*, Proc. IMDC, Athens: IMDC

ANDREWS, D J, PAWLING, R G, (2004), *Fast Motherships – a Design Challenge*, Proc. Warship 2004: Littoral Warfare & the Expeditionary Force, London: RINA

ANDREWS, D J; PAWLING, R. (2006) *The Application of Computer Aided Graphics to Preliminary Ship Design*. Ninth International Marine Design Conference (IMDC'06), volume 2. Ann Arbour, Michigan, May.

ANDREWS, D J; PAWLING, R. (2009) *A Case Study in Preliminary Ship Design*. RINA International Journal of Maritime Engineering, volume 150, 2009.

ANDREWS, DJ, (Ed.); PAPANIKOLAOU, A; ERICHSEN, S; VASUDEVAN, S. (2009) *State of the Art Report: Design Methodology*. Tenth International Marine Design Conference (IMDC'09), Trondheim, May 2009.

ANDREWS, D.; CASAROSA, L.; PAWLING, R.; GALEA, E.; DEERE, S.; LAWRENCE, P., (2008) *Integrating Personnel Movement Simulation into Preliminary Ship Design*, RINA IJME, Vol151, 2008.

ATZENI, P; CERI, S; PARABOSCHI, S; TORLONE, R. (1999) *Database Systems: Concepts, Languages and Architectures*. McGraw-Hill, London.

BETTS, CV. (2000) *Development in Ship Design from a Naval Perspective*. Seventh International Marine Design Conference (IMDC'00). Korea.

DICKS, C A, (1999), *Preliminary Design of Conventional and Unconventional Surface Ships Using a Building Block Approach*, Ph.D. Thesis, London: University of London

LONG, D; JOHNSON, S. (2007) *Case Studies in National Security Transformation: The Littoral Combat Ship From Concept to Program*. Technical Report 7, Center for Technology and National Security Policy, National Defense University, Washington,DC, March.

MAROJU, S; SYAMSUNDAR, S; DELORME, M; VASUDEVAN, S; DATLA, R; PENNOTTI, M; BRUNO, M. (2006) 'A value focused approach to ship design synthesis, analysis, and selection'. In 'World Maritime Technology Conference (WMTC2006)', The Institute of Marine Engineering, Science and Technology, London.

MCDONALD, T.P.; ANDREWS, D.J. (2009) *Hullform Comparison and Selection During Requirement Elucidation in the Concept Stage of the Ship Design Process*. Tenth International Marine Design Conference (IMDC'09). 2009.

MCDONALD, T.P.; ANDREWS, D.J. (2010) *An Advanced Demonstration of Library Based Approach to the Initial Design Exploration of Different Hullform Configurations* to be published

MINISTRY OF DEFENCE*, (1989), Classification of Weight Groups for Surface Ships,* Defence Standard NES 163 Issue 2, MoD Restricted Publication

MUNOZ, J, FORREST, C, (2002), *Advantages of Software Integration From Initial Design Through to Production Design*, Proc. ICCAS, Malmo: 2002.

PAWLING, R G, (2001), *Hyperion Class General Purpose Guided Missile Frigate*, E473 Marine Design Exercise Report, London: Department of Mechanical Engineering, UCL.

PAWLING, RG (2007) *The Application of the Design Building Block Approach to Innovative Ship Design*, PhD Thesis, University College London, 2007.

US NAVY. (2003) *Preliminary Design Interim Requirement Document for Littoral Combat Ship (LCS) Flight 0*. Technical Report N763F-S03-026, US Navy, February 2003.

Appendix J

Graphics for Communication

This appendix contains a copy of Charles Minard's 1869 flow diagram showing the losses in men, their movements, and the temperature during Napoleon's 1812 Russian campaign, from [Tufte 2001]. Tufte has stated that this "may well be the best statistical graphic ever drawn" in terms of its ability to successfully combine and display information [Tufte 2001].

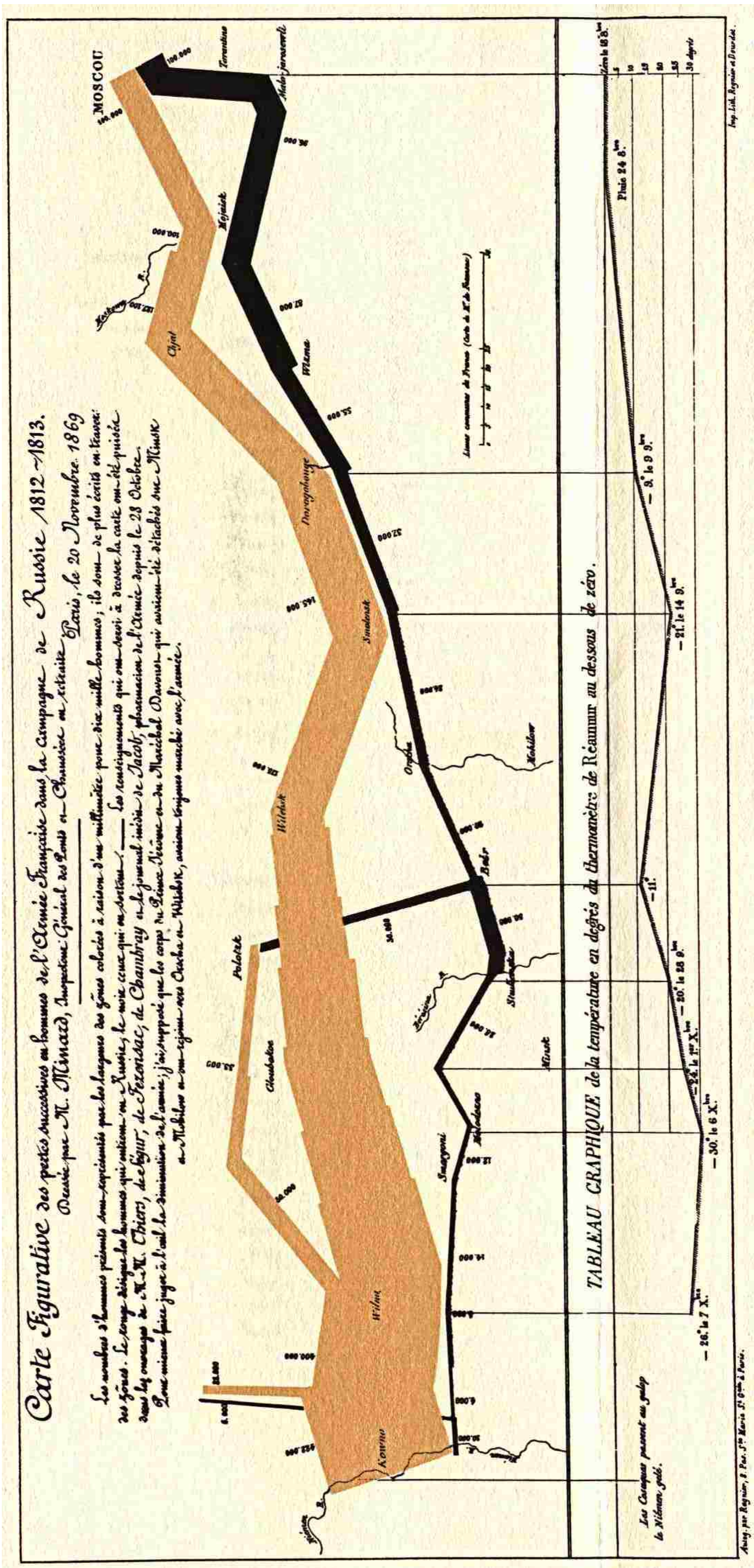


Figure J.1: Charles Minard's 1869 Chart showing the Losses in Men, their Movements, and the Temperature of Napoleon's 1812 Russian Campaign, from [Tufte 2001]